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UTILIZATION OF AMMONIA AS AN ALTERNATE FUEL IN ARMY AIRCRAFT ENGINES

By

Nicholas C. Kaños

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ABSTRACT

The successful application of the Nuclear Powered Energy Depot Concept is partly dependent upon the practicability of ammonia-fueled gas turbine engines. The purpose of this investigation was to assess the feasibility of ammonia-fueled gas turbine engines in Army aircraft. In accordance with this objective, engine performance in the UH-1D helicopter and in the CV-7A fixed-wing aircraft was compared utilizing both hydrocarbon and anhydrous ammonia fuels. Aircraft fuel system requirements were investigated, and an elementary cost comparison was made for engine conversion kits and production engines. Engine maintenance was considered briefly.

From this study, it is concluded that the use of ammonia as a gas turbine fuel results in considerably lower aircraft productivity than the productivity obtained from the use of hydrocarbon fuels.

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SYMBOLS

A	area, ft^2
c_p	specific heat, $\text{Btu/lb } ^\circ\text{F}$
D	outside diameter, in.
d	inside diameter, in.
k	thermal conductivity, $\text{Btu/hr ft}^2 ^\circ\text{F/ft}$
L	length, ft
l	length, in.
l_{tk}	tank length, in.
q	heat flow rate, Btu/hr
T	temperature, $^\circ\text{F}$
t	time, hr
th	thickness, ft or in.
W	gross weight, lb
W_A	ammonia weight, lb
W_E	empty tank weight, lb
W_F	fuel weight, lb
W_S	fuel system weight, lb
W_T	gross weight (tank + fuel), lb
ΔT	difference in temperature, $^\circ\text{F}$
ϵ	regenerator effectiveness, pct
ρ	density, lb/ft^3

INTRODUCTION

The logistics problems associated with the supply of fuel to advanced base areas during combat operations are often formidable. If the proper equipment were available in these forward areas, fuel could be "manufactured" from the natural elements of nitrogen and hydrogen. Since air is composed of about 78 percent nitrogen, and since hydrogen is obtainable from any supply of water, ammonia (NH_3) can be produced. The use of ammonia as a fuel has been proven feasible, despite certain penalties and problems associated with its use that must be considered.

This report deals with the particular penalties and problems that would be encountered with the use of ammonia in typical gas turbine-powered Army aircraft. A rotary-wing (UH-1D) aircraft and a fixed-wing (CV-7A) aircraft were chosen for study to provide a comparison of the effects of ammonia in two distinct types of Army aircraft.

Included in this comparison are the effects of ammonia on engine performance and engine weight, on the aircraft fuel system and aircraft empty weight, on aircraft range-payload characteristics, and on cost of equipment installation and maintenance. An outline of the basic assumptions made and the methods of analysis used during this study is also included.

BASIC ASSUMPTIONS

Aircraft operating weights for the nonregenerative hydrocarbon-fueled (JP-4 $\epsilon = 0$), the regenerative hydrocarbon-fueled (JP-4 $\epsilon = 75$ percent), the nonregenerative ammonia-fueled (NH₃ $\epsilon = 0$), and the regenerative ammonia-fueled (NH₃ $\epsilon = 75$ percent) configurations are shown in Table I for the UH-1D helicopter and the CV-7A fixed-wing aircraft.

TABLE I
AIRCRAFT OPERATING WEIGHTS

Configuration	UH-1D (lb)	CV-7A (lb)
JP-4 $\epsilon = 0$	5,000	23,200
JP-4 $\epsilon = 75\%$	5,300	not considered
NH ₃ $\epsilon = 0$	5,100	23,450
NH ₃ $\epsilon = 75\%$	5,500	25,200

The operating weight of each configuration of the UH-1D consists of a 200-pound pilot and 31 pounds of trapped liquids. The regenerative configurations consist of an additional weight of 400 pounds for the regenerator and additional engine installation hardware. In the case of the ammonia-fueled configurations, there was an additional engine weight of 100 pounds. The operating weight of each configuration of the CV-7A consists of a 600-pound crew (pilot and two crew members) and 70 pounds of trapped liquids. The regenerative configurations consist of an additional weight of 1,750 pounds for the two regenerators and additional engine installation hardware. In the case of the ammonia-fueled configurations, there was an additional engine weight of 250 pounds for the two engines.

Fuel system weights of the ammonia-fueled craft were determined from the fuel system weight curves presented in this report and from the total mission fuel requirements. All aircraft operating weights presented contained the hydrocarbon fuel system weight. This fuel system weight was not removed from the ammonia-fueled craft, since it was assumed that the craft would have a multifuel capability; that is, by means of a simple

valving system, the engine could operate with either hydrocarbon or ammonia fuels.

A quick survey was made to determine the aircraft C. G. location at the design gross-weight conditions. In the case of the UH-1D, it was determined that cylindrical tanks had to be used in order to maintain the C. G. aft of station 129, which is the forward C. G. limit. If a spherical tank having a capacity equal to the cylindrical tank were used, its larger diameter would cause the helicopter C. G. to shift into the forward C. G. critical limit range. In some cases in this investigation, it was assumed that the C. G. limits would prevent the craft from carrying a full payload. In the case of the CV-7A aircraft, which has a larger cargo compartment, the fuel tanks could be placed to maintain the aircraft C. G. within the critical limits at all times. Arrangement of payloads in the fixed-wing craft may impose a problem, because of the large fuel tanks located near the C. G. of the craft.

The mission used for the helicopter engine evaluation is defined as follows:

1. Warm-up and takeoff allowances: 7 minutes of normal rated power at sea level (two takeoffs, initial and midpoint).
2. Cruise out: sea level, at designated cruise speeds.
3. Land at remote base (no change in payload).
4. Cruise back: sea level, at designated cruise speeds.
5. Reserve allowance: 10 percent of initial fuel load.

The mission used for the fixed-wing aircraft engine evaluation is defined as follows:

1. Warm-up and takeoff allowances: 10 minutes of normal rated power at sea level (two takeoffs, initial and midpoint).
2. Cruise out: sea level, at designated cruise speeds.
3. Land at remote base (no change in payload).
4. Cruise back: sea level, at designated cruise speeds.
5. Reserve allowance: 10 percent of initial fuel load.

A single-view drawing of the UH-1D and a three-view drawing of the CV-7A are shown in Figures 1 and 2, respectively.

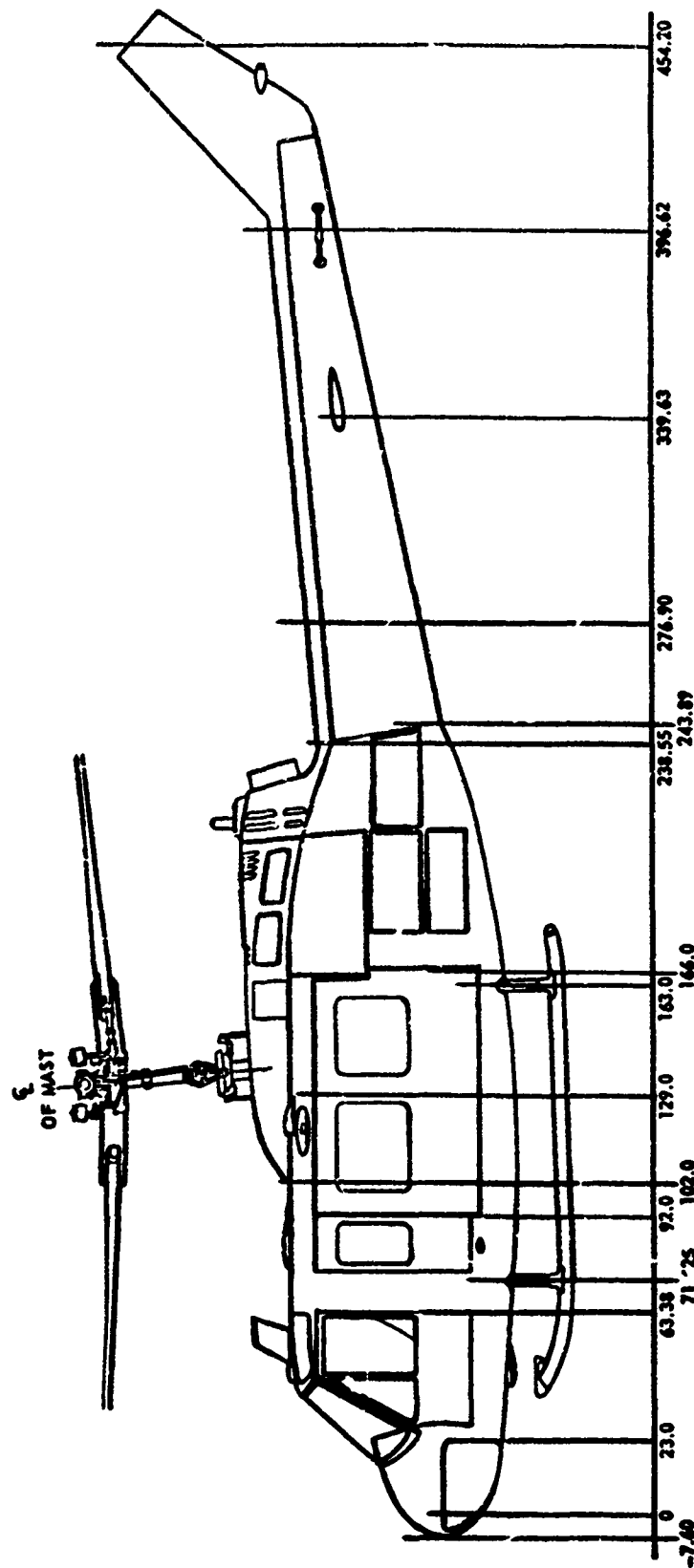


Figure 1. UH-1D Station Diagram.

AMMONIA FUEL TANKS AND AIRCRAFT FUEL SYSTEMS

The boiling point of anhydrous ammonia at atmospheric pressure is -28°F . The freezing point is -108°F . Ammonia must therefore be stored in pressurized and/or refrigerated vessels. The high coefficient of thermal expansion permits only partial filling of the container, to avoid failure under hydrostatic pressure. Section 73.315(a) of Shipper Rules and Regulations states that unlagged cargo tanks and portable tank containers for liquid anhydrous ammonia may be filled to 87.5 percent by volume, provided that the temperature of the anhydrous ammonia being loaded into such tanks is determined to be not lower than $+30^{\circ}\text{F}$, or provided that the filling of such tanks is stopped at the first indication of frost or ice formation on the outside surface of the tank and is not resumed until such frost or ice has disappeared.* Therefore, the maximum permitted filling density of 87.5 percent by volume was used in the design of all tanks.

Two types of materials were considered for construction of lightweight, high-pressure fuel tanks: steels and fiber-glass-reinforced plastics. Fiber glass is more attractive for the construction of smaller tanks, in which the wall thickness is dictated by handling and the possibility of mechanical damage rather than stress. Steels were assumed to be best for large-size tanks, in which wall thickness of 0.100 inch or more is required. In order to complete a typical aircraft mission, the fuel tank capacity is considered to be relatively large. Therefore, only steel fabrication was considered to be applicable to this study.

The selection of a suitable material to meet the requirements of a pressurized ammonia fuel tank was, in part, guided by the report of Moran, Mihensen, and Skinner.** It is apparent from the report that certain stainless and nickel alloy steels resist most highly the corrosive action caused by the nitrogen in ammonia. Of those investigated, the two types of steel which offered the greatest resistance to corrosion were AISI 330

*T. C. George, "Agent T. C. George's Tariff No. 15, Interstate Commerce Commission Rules and Regulations", September 1963, pp. 92-96.

**J. J. Moran, J. R. Mihensen, and E. N. Skinner, "Behavior of Stainless Steels and Other Engineering Alloys in Hot Ammonia Atmospheres", Corrosion 17, Number 4, April 1961, pp. 115-119.

stainless steel and Inconel alloy. The Inconel alloy offers the greatest resistance. An important notation is that the nickel-base alloys in the iron-nickel-chromium systems are substantially more resistant to attack by nitrogen than those alloys richer in iron and chromium. Polished surfaces are even more resistant. Taking all considerations into account, Inconel alloy 600, having a density of 0.307 pound per cubic inch and an ultimate tensile strength of 80,000 psi, was selected.

Two basic fuel tank designs were investigated: spherical, and cylindrical with spherical ends. Tank configurations are shown in Figure 3. Typical cylindrical and spherical tank baffles are shown in Figures 4 and 5, respectively. In order for ammonia to be maintained in a liquid state at a given temperature, its vapor pressure must equal or exceed the pressure shown in Figure 6. For example, if ammonia is to be stored at a temperature of 50°F, its vapor pressure must be 75 psig or greater; or, at a temperature of 165°F, its vapor pressure must be 515 psig or greater. In a hot stagnant environment, such as the cargo compartment of an aircraft, the temperature could reach 165°F. Therefore, in tanks designed for the storage of ammonia in aircraft cargo compartments, the NH_3 vapor pressure must be equal to or greater than 515 psig.

In accordance with this requirement, a 500-psig vapor or tank working pressure was selected as a design consideration to be used in the aircraft performance studies. A second working pressure of 75 psig was also selected, in order to compare aircraft performance with the use of both relatively low- and high-pressure tank designs.

From previous research in gelation of hydrocarbon fuels for flight safety, it became apparent that gelation of ammonia fuels through the use of an additive might be feasible. Experience has shown that the gelation of other low-boiling materials such as naphthas, ethers, and chlorinated compounds will not lower the vapor pressure of the material being gelled. Gelation will, however, decrease the rate of vaporization.

It is anticipated that gelation will not eliminate the heavy tanks needed to store ammonia, but it may simplify the handling problem, because it will retard the rate of vaporization. In turn, it is believed that the boiling point of -28°F for anhydrous ammonia will increase, which will reduce the refrigeration requirements of nonpressurized containers.

Storage of ammonia may be accomplished with refrigerated or nonrefrigerated tanks. Storage of ammonia in nonrefrigerated tanks, resulting in high vapor pressures, is discussed in the following section.

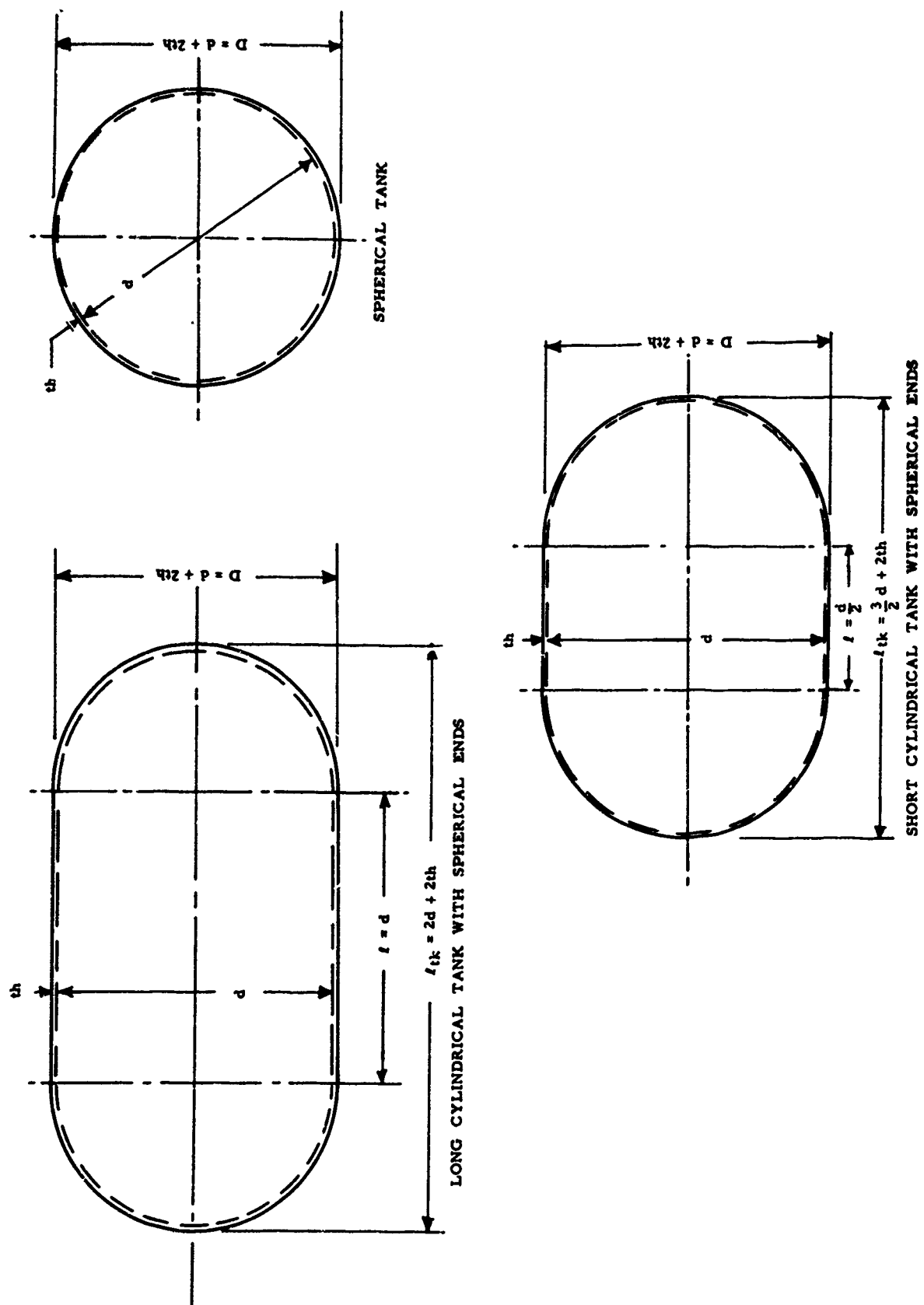


Figure 3. Tank Configurations.

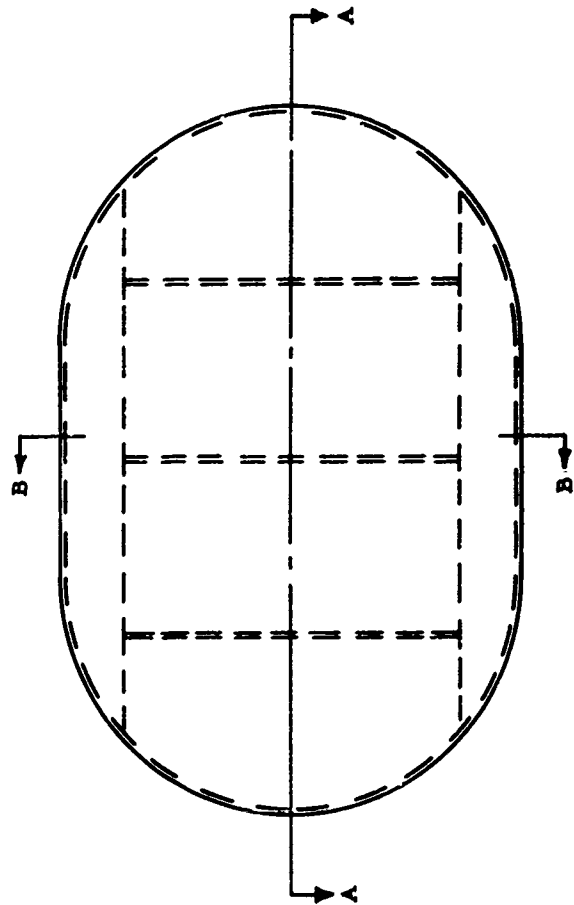
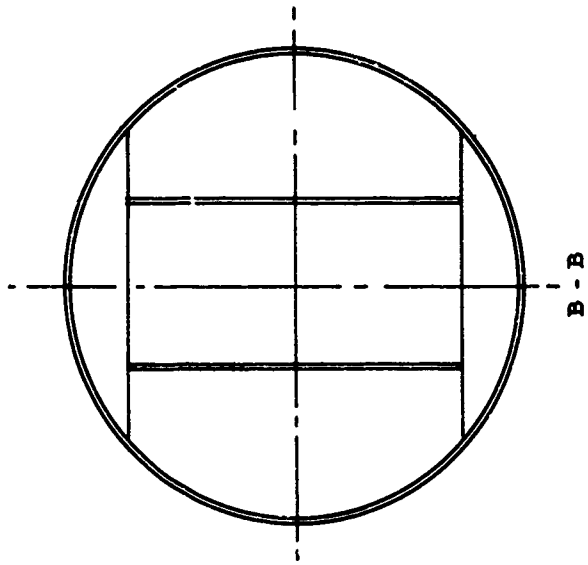
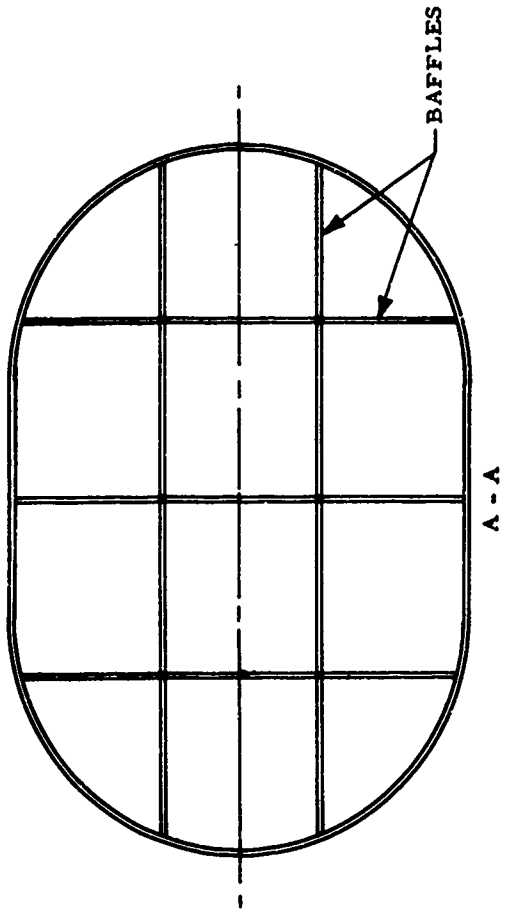


Figure 4. Cylindrical Tank Baffles.

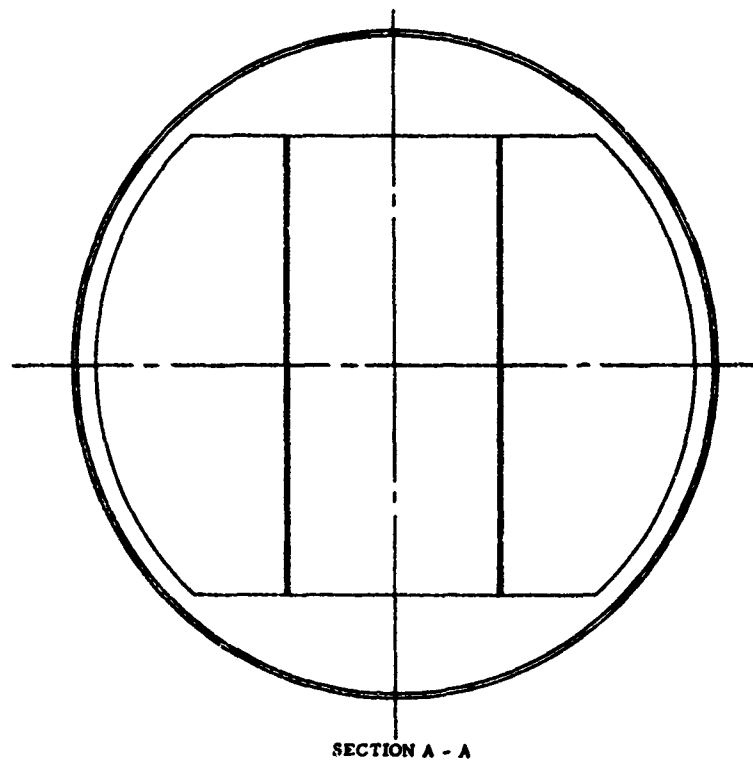
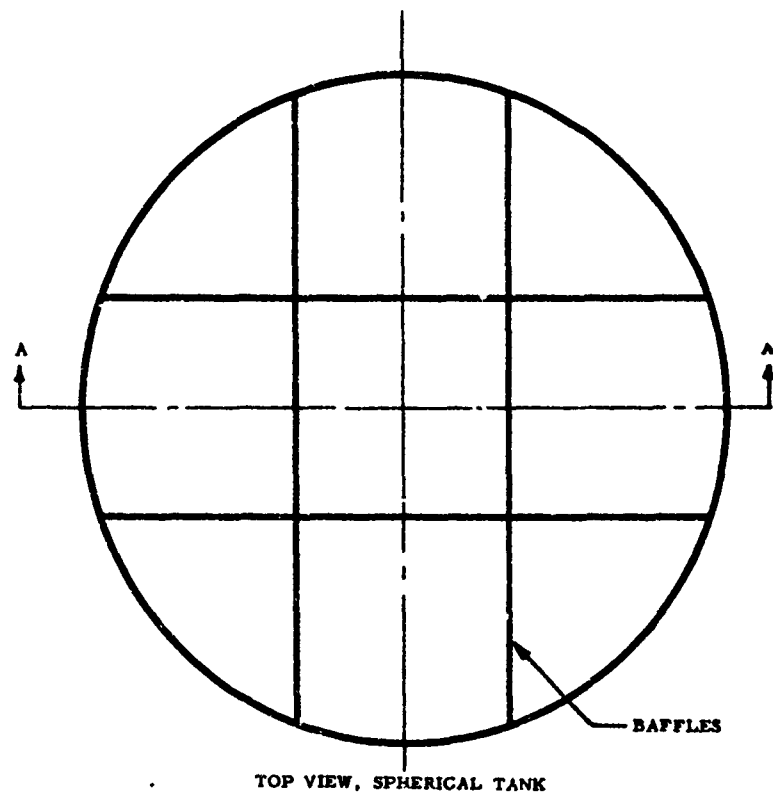


Figure 5. Spherical Tank Baffles.

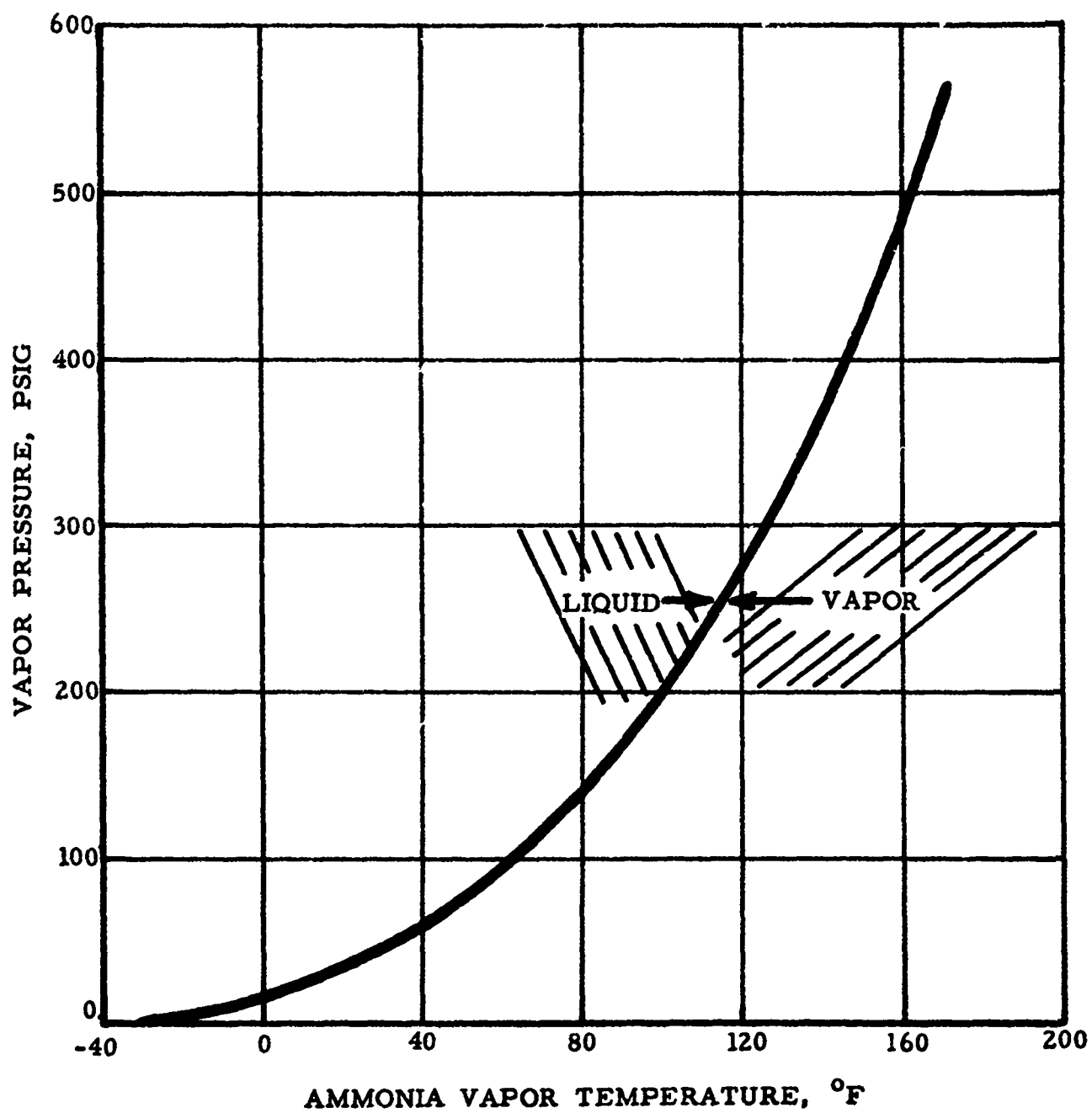


Figure 6. Ammonia Temperature Versus Pressure.

HIGH-PRESSURE TANKS

Tables II and III show the design characteristics of spherical, cylindrical, short, and long tanks of various capacities, based on a working pressure of 500 psig. The design pressure of these tanks is 2.5 times the working pressure. The 2.5 safety factor was obtained from MIL-T-7378A.* This specification states that the tanks must withstand a hydrostatic pressure of not less than 2.5 times the maximum operating pressure (working pressure) encountered under all conditions. The pertinent data from Tables II and III are plotted in Figures 7 and 8.

From Figure 7, it can be seen that the short cylindrical tank is slightly heavier than the long tank; and since it does not offer any advantages in aircraft installation (aircraft C. G. location), it will not be considered for use in the aircraft performance studies.

An interesting note from Figure 8 is that the ratio of tank weight to fuel weight is constant for a given pressure and varying tank capacity. Figure 9 shows the ratio of tank weight to fuel weight plotted against a varying working pressure. Therefore, as shown in Figure 8, the weight ratios of any working pressure will remain constant for any tank capacity.

The ratio of aircraft fuel system weight to fuel weight versus working pressure is shown in Figure 10. The fuel system weight is made up of tank, base, piping, etc. Typical fuel tank installations in the UH-1D and CV-7A are shown in Figures 11 and 12, respectively. Each tank should have a pressure and temperature gauge (shown in Figures 11 and 12 as PG and TG), and a temperature versus pressure chart reflecting information given in Figure 6. Each tank should also be equipped with at least two preset pressure-relief valves for safety and a fuel transfer pump for low-temperature and low-pressure operation.

A quick cost estimate of spherical and long cylindrical tanks was conducted, with the results shown in Figure 13. Cost of instruments and fuel transfer pump is not included in the estimates.

*MIL-T-7378A (USAF), "Military Specification: Tanks, Fuel, Aircraft, External, Auxiliary, Removable", October 1958, Sec. 3.7.6., p. 12.

AMMONIA-FILLED SPHERICAL FUEL

FUEL CAPACITY (GALLONS)*	25	50	75	100	125	150	175	200	225	250
TANK CAPACITY (VOLUME)	28.5	57.1	85.7	114.2	142.8	171.4	200.0	228.5	257.1	285
TANK VOLUME (CUBIC IN.)	6,600	13,200	19,800	26,400	33,000	39,600	46,200	52,800	59,400	66,000
d	23.375	29.375	33.625	37.000	39.750	42.250	44.500	46.500	48.375	50.000
th	.091	.115	.131	.145	.155	.165	.174	.182	.189	.196
D	23.557	29.605	33.887	37.290	40.060	42.580	44.848	46.864	48.753	50.500
W _E	49	96	145	194	240	289	338	386	433	482
W _A **	129	258	387	516	645	774	903	1032	1161	1290
W _T	178	354	532	710	885	1063	1241	1418	1594	1770
$\frac{W_E}{W_A}$	.380	.372	.375	.376	.372	.373	.374	.374	.373	.370

*BASED ON MAXIMUM FILLING DENSITY OF 87.5% BY VOLUME.

**DENSITY OF AMMONIA BASED ON 60° F = 5.15 POUNDS PER GALLON

TABLE II
AMMONIA-FILLED SPHERICAL FUEL TANKS, DESIGN CHARACTERISTICS

TANKS,

FUEL		125	150	175	200	225	250	275	300	325	350	375	400
250													45
285	2	142.8	171.4	200.0	228.5	257.1	285.7	314.2	342.8	371.4	400.0	428.5	457.1
66,	00	33,000	39,600	46,200	52,800	59,400	66,000	72,600	79,200	85,800	92,400	99,000	1,056,000
50.	00	39.750	42.250	44.500	46.500	48.375	50.125	51.750	53.125	54.750	56.125	57.375	58.750
.19		.155	.165	.174	.182	.189	.196	.202	.208	.214	.219	.224	.229
50.	90	10.060	12.580	14.848	16.864	18.753	20.517	22.154	23.541	25.178	26.563	27.823	29.154
482		240	289	338	386	433	482	530	575	628	676	722	769
129	1	645	774	903	1032	1161	1290	1419	1548	1677	1806	1935	2064
177	1	885	1063	1241	1418	1594	1772	1949	2123	2305	2482	2657	2834
.37		.372	.373	.374	.374	.373	.374	.374	.371	.374	.374	.373	.374

...LLING DENSITY OF 87.5% BY VOLUME.

BASED ON 60° F = 5.15 POUNDS PER GALLON.

DESIGN PRESSURE = 2.5 × WC

B

II NKS, DESIGN CHARACTERISTICS

	300	325	350	375	400	425	450	475	500	
4.2	342.8	371.4	400.0	428.5	457.1	485.7	514.2	542.8	571.4	
1600	79,200	85,800	92,400	99,000	105,600	112,200	118,800	125,400	132,000	
5750	53.125	54.750	56.125	57.375	58.750	59.875	61.000	62.125	63.250	
.02	.208	.214	.219	.224	.230	.234	.238	.243	.247	
.154	53.541	55.178	56.563	57.823	59.210	60.343	61.476	62.611	63.744	
.00	575	628	676	722	778	822	868	919	968	
.09	1548	1677	1806	1935	2064	2193	2322	2451	2580	
.49	2123	2305	2482	2657	2842	3015	3190	3370	3548	
.04	.371	.374	.374	.373	.377	.375	.374	.375	.375	AVERAGE .374

WC

DESIGN PRESSURE = 2.5 × WORKING PRESSURE (500 PSIG) = 1,250 PSIG.

C

TABLE III
AMMONIA-FILLED CYLINDRICAL FUEL TANKS

FUEL CAPACITY (GALLONS)	25	50	75	100	125	150	175	200	225	250	275
TANK CAPACITY (GALLONS)	28.5	57.1	85.7	114.2	142.8	171.4	200.0	228.5	257.1	285.7	314.3
TANK VOLUME (CUBIC INCHES)	6600	13,200	19,800	26,400	33,000	39,600	46,200	52,800	59,400	66,000	72,600
A. LONG CYLINDRICAL TANK WITH RICA											
$d = l$	17.250	21.625	24.750	27.250	29.375	31.125	32.875	34.375	35.750	37.000	38.250
th	.135	.169	.193	.213	.229	.243	.257	.269	.279	.289	.297
D	17.520	21.963	25.136	27.676	29.833	31.611	33.389	34.913	36.308	37.578	38.730
l_{tk}	34.770	43.588	49.886	54.926	59.208	62.736	66.264	69.288	72.058	74.578	76.808
W_E	78	153	228	305	381	454	536	613	688	763	838
W_A	129	258	387	516	645	774	903	1032	1161	1290	1419
W_T	207	411	615	821	1026	1228	1429	1645	1849	2053	2254
$\frac{W_E}{W_A}$	.605	.593	.589	.591	.591	.587	.594	.594	.593	.591	.589
B. SHORT CYLINDRICAL TANK WITH RICA											
$d = 2l$	19.375	24.375	27.875	30.750	33.000	35.125	37.000	38.625	40.250	41.625	43.000
l	9.688	12.187	13.938	15.375	16.500	17.563	18.500	19.313	20.125	20.813	21.500
th	.151	.190	.218	.240	.258	.274	.289	.302	.314	.325	.336
D	19.677	24.755	28.311	31.230	33.516	35.673	37.578	39.229	40.878	42.275	43.678
l_{tk}	29.365	36.942	42.249	46.605	50.016	53.236	56.078	58.542	61.003	63.088	65.100
W_E	82	163	245	328	407	489	573	652	736	802	899
W_A	129	258	387	516	645	774	903	1032	1161	1290	1419
W_T	211	421	632	844	1052	1263	1476	1684	1897	2092	2318
$\frac{W_E}{W_A}$	.636	.632	.633	.636	.631	.632	.635	.632	.634	.622	.634

III TABLE III
 ANNUAL FUEL TANKS, DESIGN CHARACTERISTICS

27.25	250	275	300	325	350	375	400	425	450	475	500	
31.1	285.7	314.2	342.8	371.4	400.0	428.5	457.1	485.7	514.2	542.8	571.4	
72,400	66,000	72,600	79,200	85,800	92,400	99,000	105,600	112,200	118,800	125,400	132,000	
WITH RICAL TANK WITH SPHERICAL ENDS												
38.750	37.000	38.125	39.125	40.375	41.375	42.375	43.375	44.125	45.000	45.875	46.625	
.2879	.289	.298	.306	.315	.323	.331	.339	.345	.352	.358	.364	
39.308	37,578	38.721	39.737	41.005	42.021	43.037	44.053	44.815	45.704	46.591	47.353	
76.058	74.578	76.846	78.862	81.480	83.396	85.412	87.428	88.940	90.704	92.466	93.978	
83.38	763	836	904	991	1067	1147	1230	1296	1375	1453	1526	
141.61	1290	1419	1548	1677	1806	1935	2064	2193	2322	2451	2580	
225.49	2053	2255	2452	2668	2873	3082	3294	3489	3697	3904	4106	
.58993	.591	.589	.584	.591	.591	.593	.596	.591	.592	.593	.591	AVERAGE .592
K WITH RICAL TANK WITH SPHERICAL ENDS												
43.250	41.625	43.000	44.125	45.500	46.625	47.625	48.750	49.625	50.625	51.625	52.500	
21.5175	20.813	21.500	22.063	22.750	23.313	23.813	24.375	24.813	25.313	25.813	26.250	
.33614	.325	.336	.345	.355	.364	.372	.381	.388	.396	.403	.410	
43.6878	42.275	43.672	44.815	46.210	47.353	48.369	49.512	50.401	51.417	52.431	53.320	
65.1003	63.088	65.172	66.878	68.960	70.666	72.182	73.887	75.214	76.730	78.244	79.570	
899.5	802	899	972	1063	1145	1221	1310	1382	1468	1554	1635	
141.61	1290	1419	1548	1677	1806	1935	2064	2193	2322	2451	2580	
231.37	2092	2318	2520	2740	2951	3156	3374	3575	3790	4005	4215	
.63414	.622	.634	.628	.634	.634	.631	.635	.631	.632	.634	.634	AVERAGE .633

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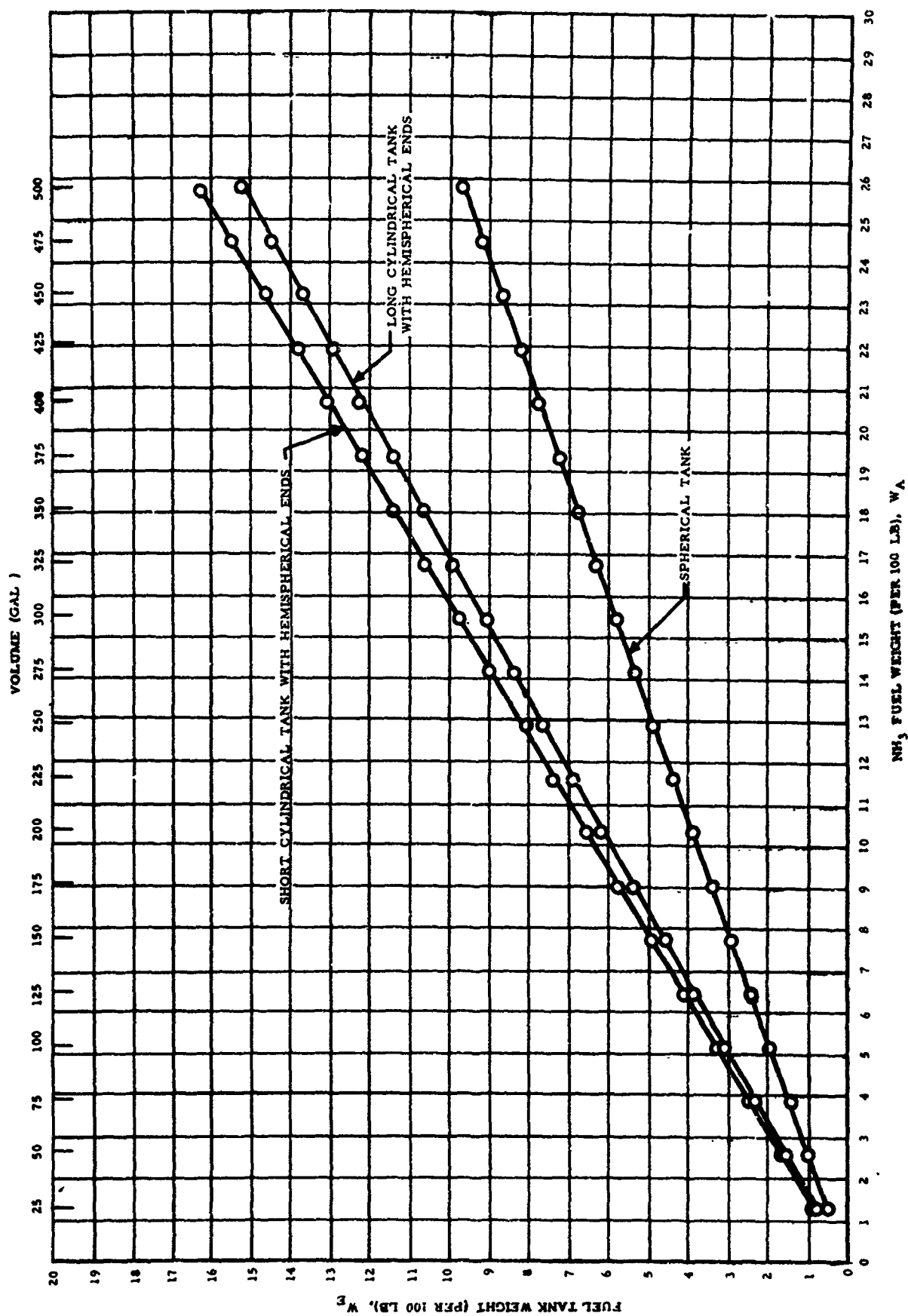


Figure 7. Ammonia Fuel Tanks, Fuel Tank Weight Versus Fuel Weight.

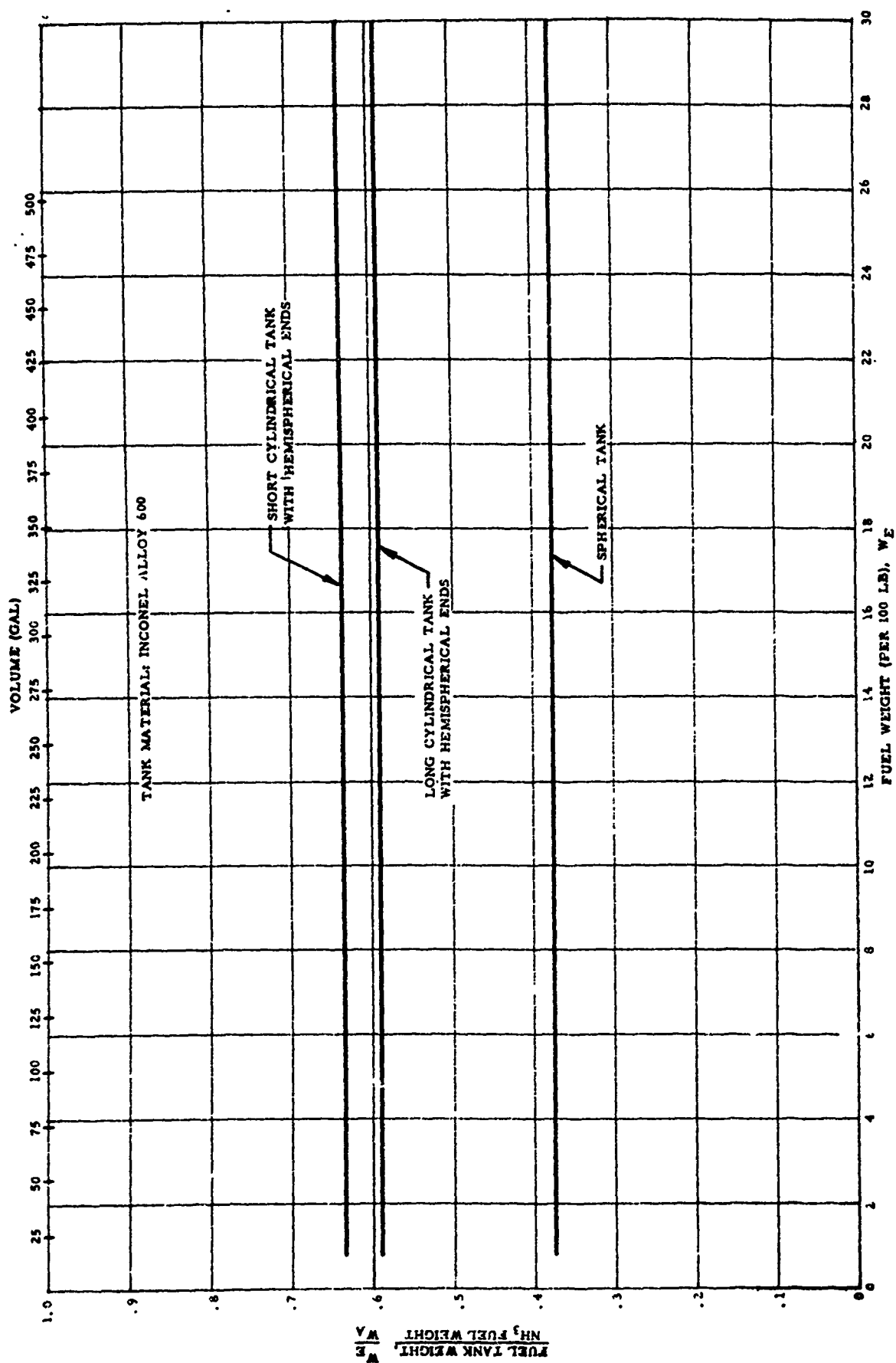


Figure 8. Ammonia Fuel Tanks, $\frac{\text{Fuel Tank Weight}}{\text{Fuel Weight}}$ Versus Fuel Weight and Volume.

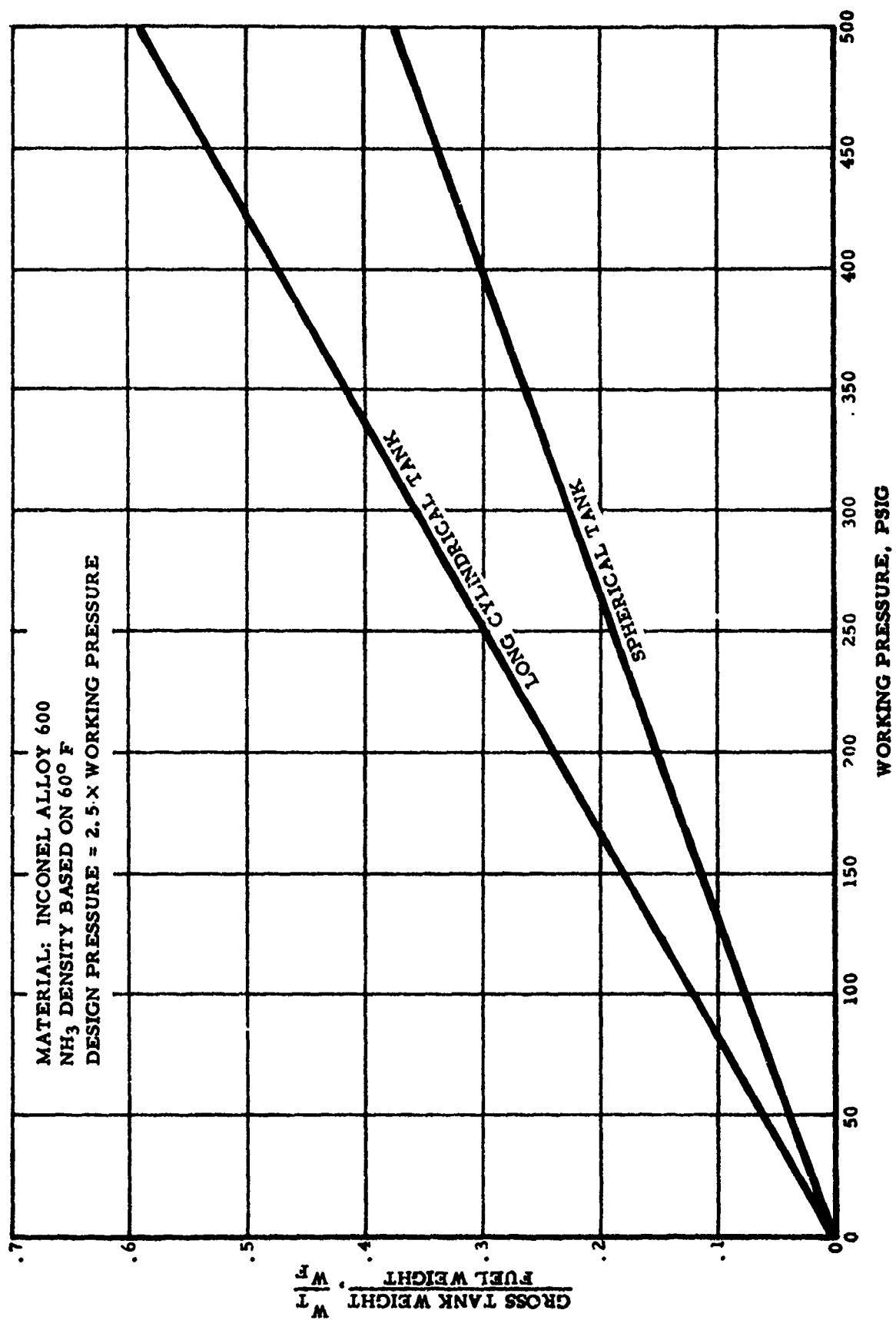


Figure 9. Ammonia Fuel Tanks, Pressure Versus $\frac{\text{Tank Weight}}{\text{Fuel Weight}}$.

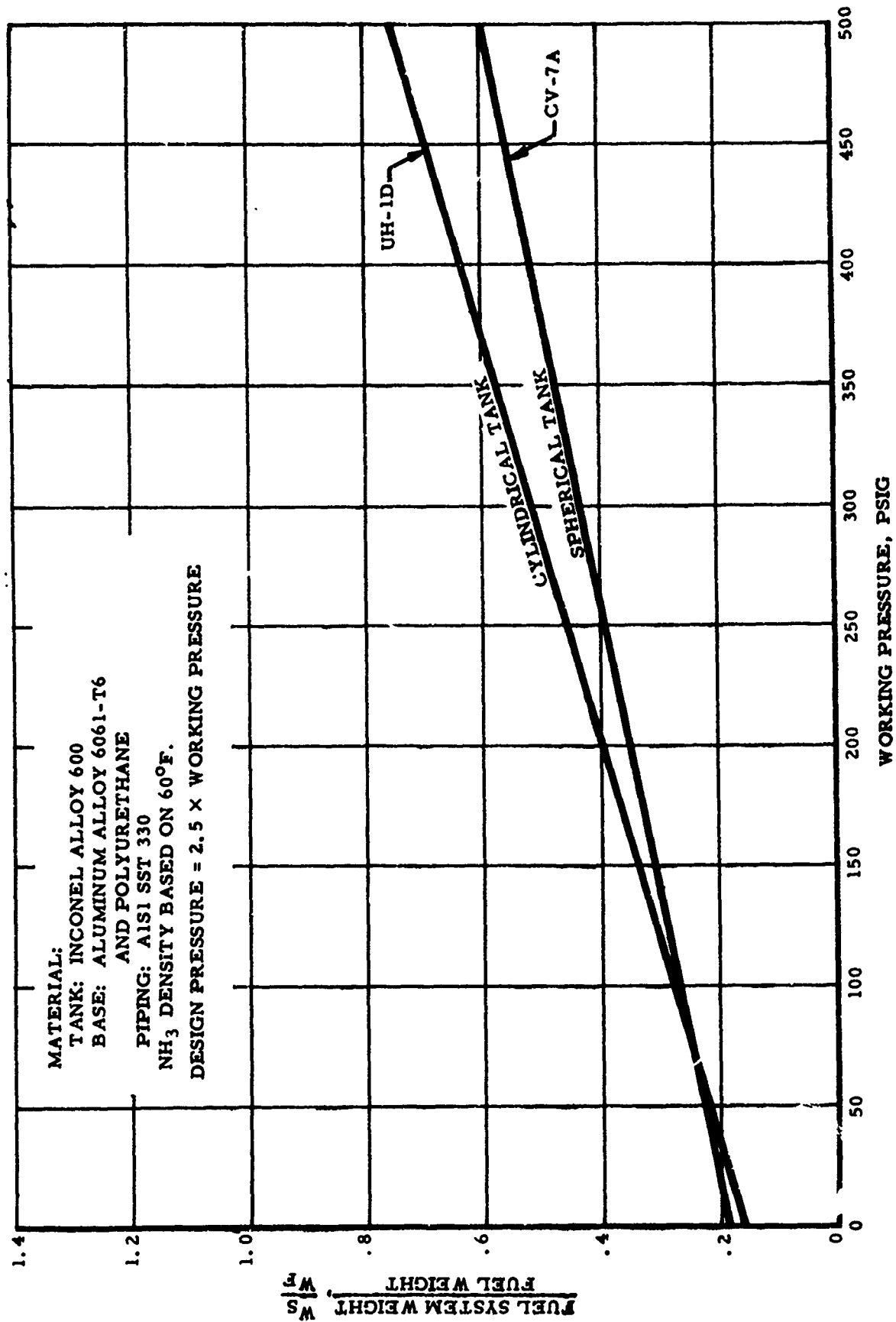


Figure 10. Ammonia Fuel Tanks, Pressure Versus $\frac{\text{Fuel System Weight}}{\text{Fuel Weight}}$

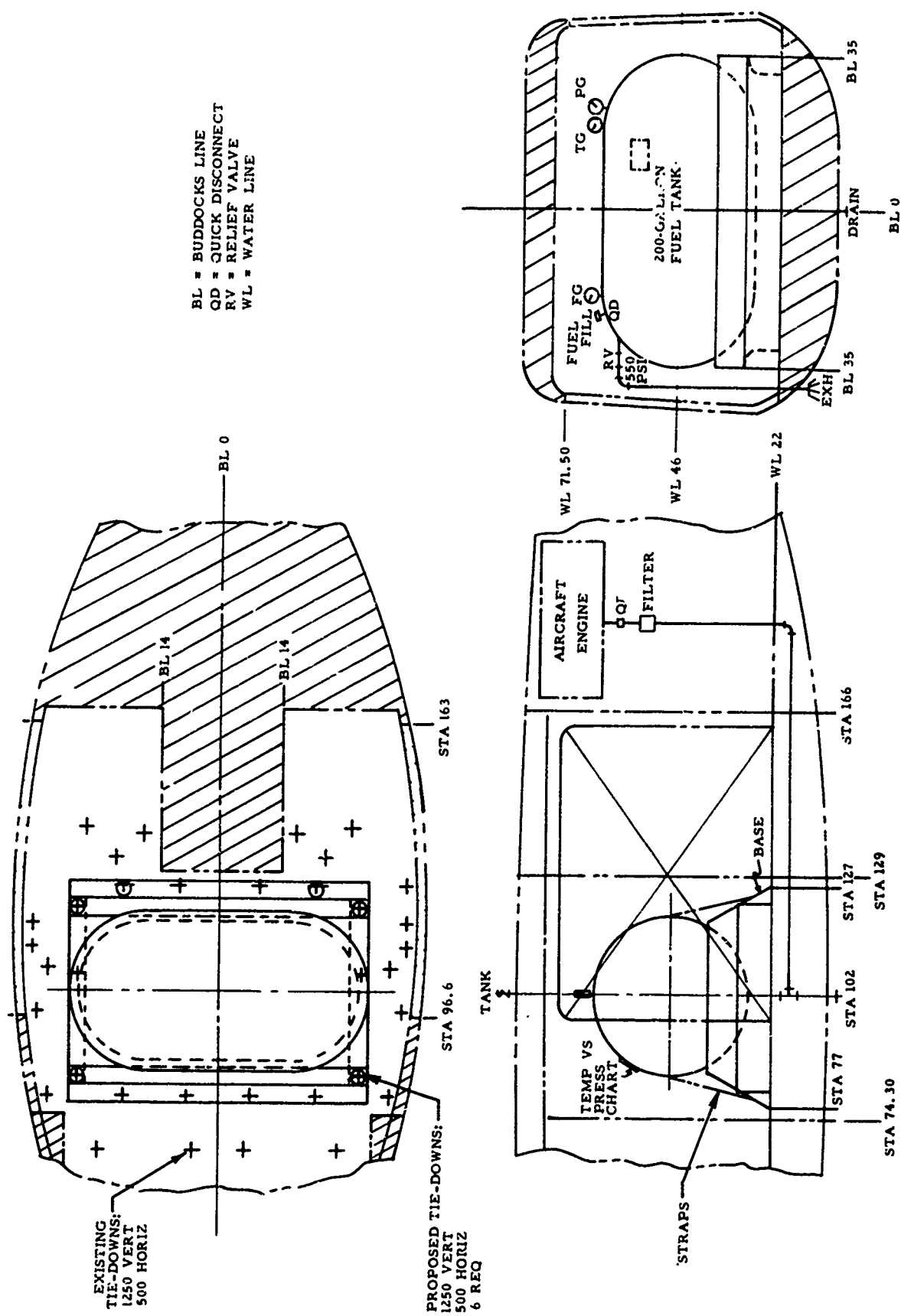


Figure 11. UH-1D Cargo Area.

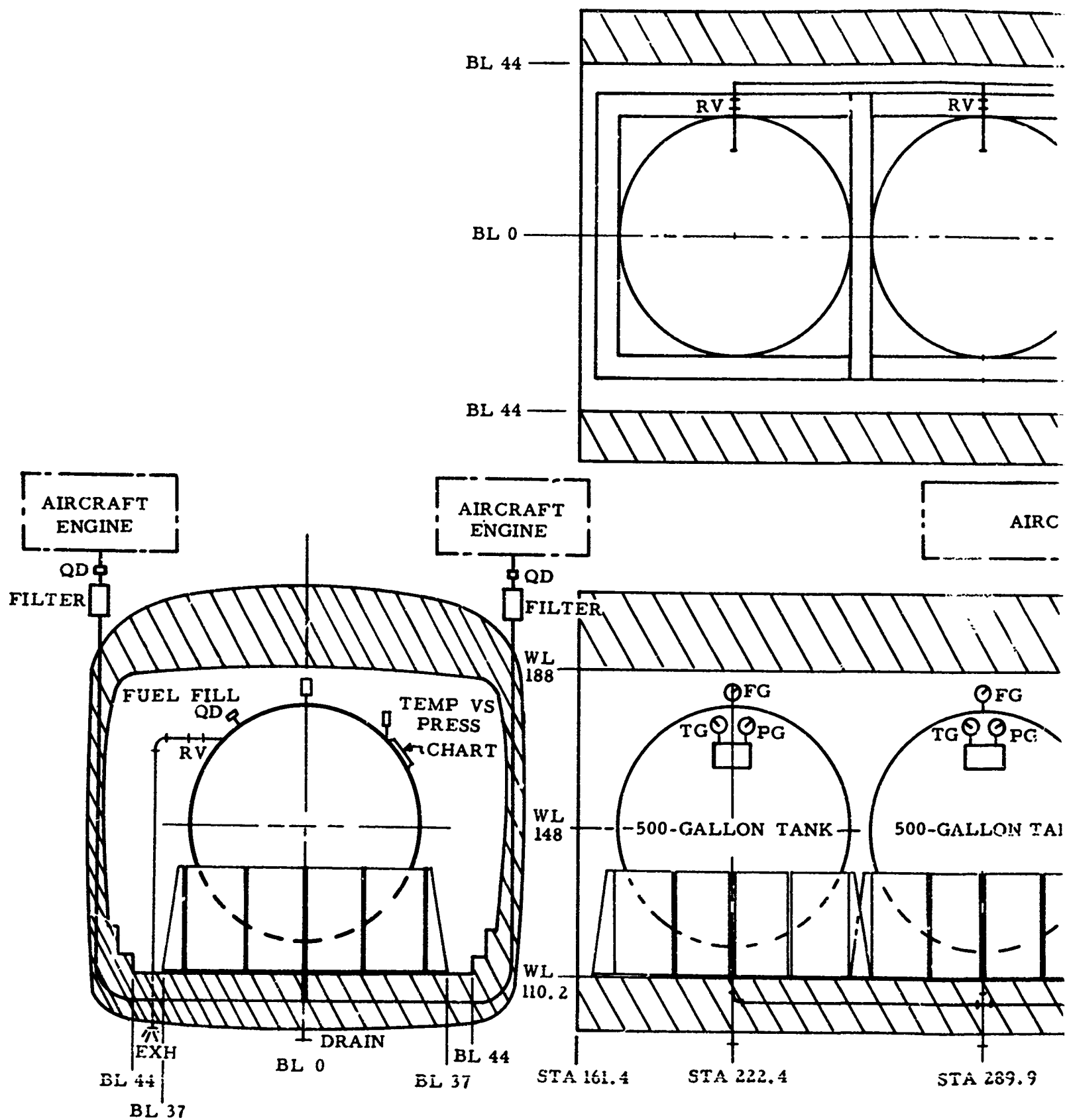
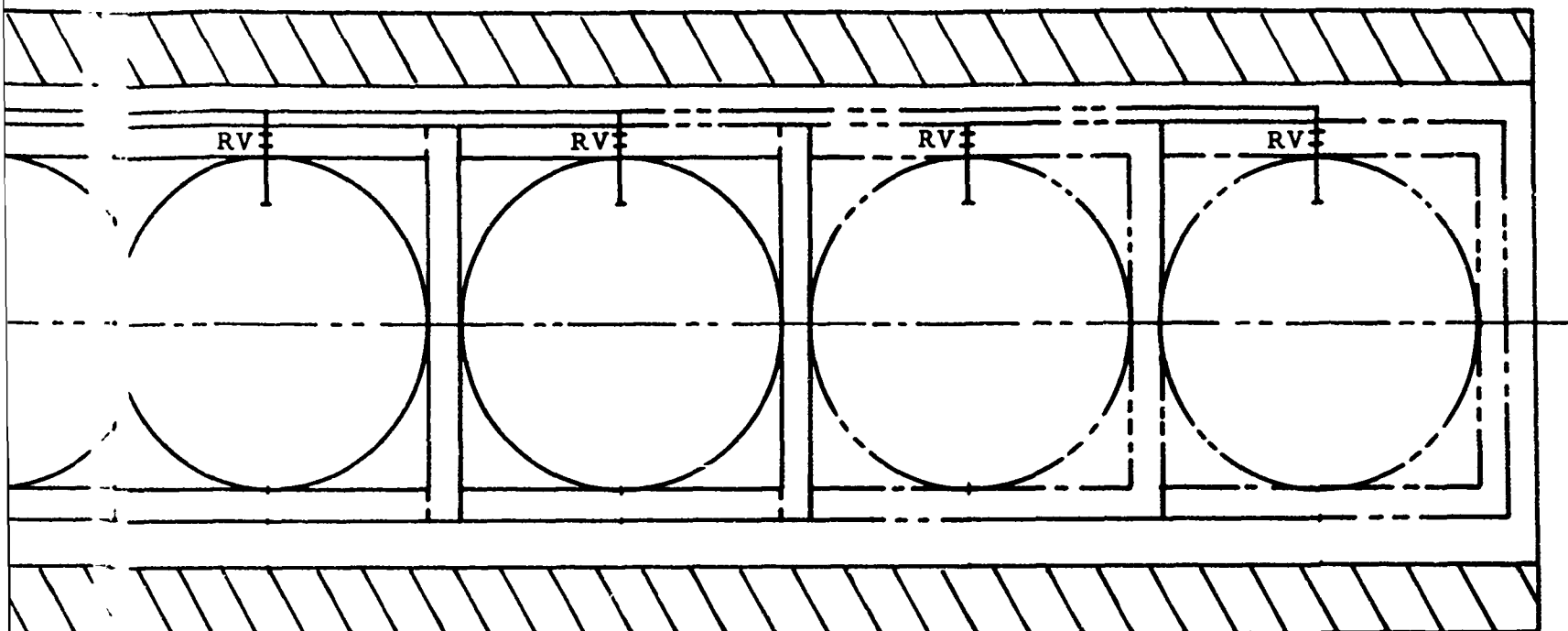
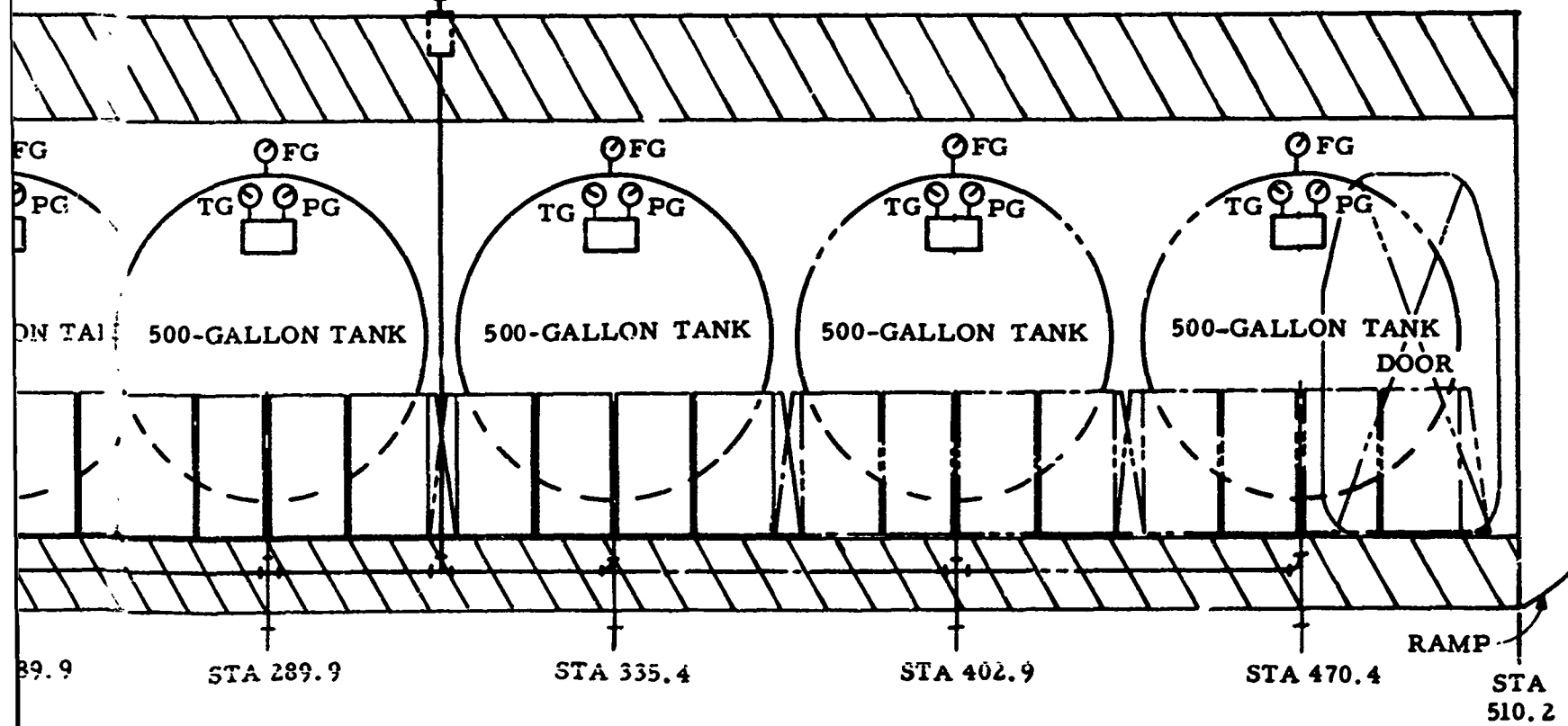


Figure 12. CV-7A Cargo Area.



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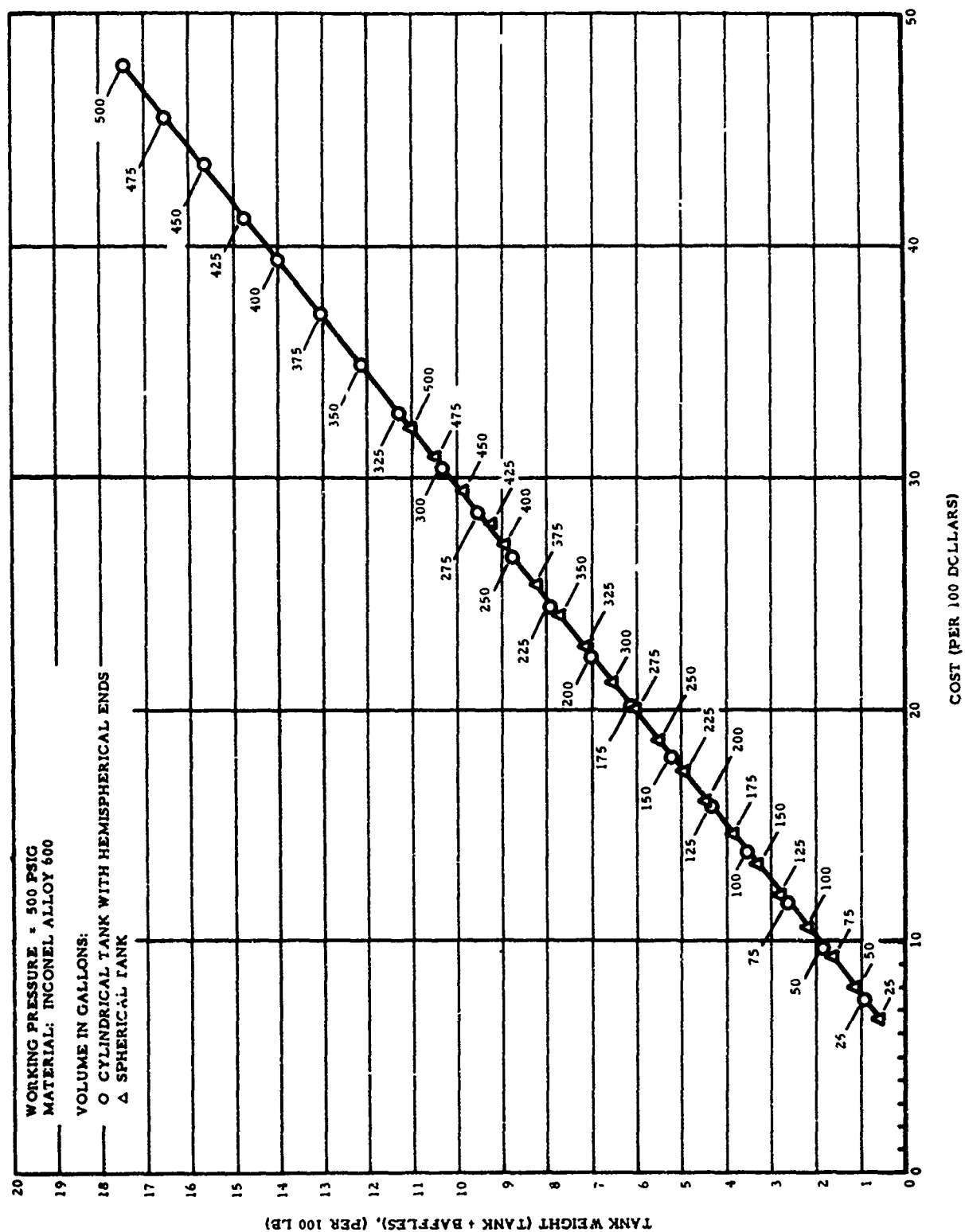


Figure 13. Ammonia Fuel Tanks, Cost Versus Tank Weight.

LOW-PRESSURE TANKS

In this section, methods of low-pressure tank storage are discussed, accomplished either by the use of refrigerated tanks or by refrigerated ammonia in heavily insulated storage tanks for long-time storage.

One of the most attractive methods for storing large quantities of ammonia is the use of nonpressurized containers. The ammonia is maintained at approximately -28°F by the refrigeration resulting from ammonia evaporation. The ammonia vapor may be recondensed in auxiliary equipment for long-term storage. The use of low-pressure insulated tanks for aircraft applications appears to have some advantages, if the approach and assumptions are accepted. The ammonia would be delivered to the aircraft tank from the bulk storage at -28°F and atmospheric pressure. By insulating the fuel tank to reduce heat inflow and by using the ammonia as a heat sink, the ammonia could be maintained at a low temperature, and losses due to vaporization could be minimized.

A 100-gallon, long cylindrical tank has been selected to demonstrate this principle. From Table III, it can be seen that a tank having an allowable ammonia capacity of 100 gallons will have a capacity of 26,400 cubic inches, an outside diameter of 27.50 inches, and an overall length of 54.75 inches at a 75-psig working pressure. Assume that there is 1 inch of felted fiber glass insulation with a density of 0.5 pound per cubic foot and a thermal conductivity of $0.023 \text{ Btu/hr ft}^2 \text{ }^{\circ}\text{F/ft}$. The weight of this insulation would be 1.395 pounds, which can be considered negligible.

$$W = A \times th \times \rho = 33.45 \times .083 \times 0.5 = 1.395 \text{ lb} \quad (1)$$

where

A is tank surface area.

th is insulation thickness.

ρ is insulation density.

A tank vent valve would be installed as a safety measure, but in order to minimize loss caused by vaporization, this valve would not open during a normal mission. This establishes the upper temperature limit of the ammonia fuel remaining in the tank at the end of the mission. The 75-psig allowable working pressure for the tank corresponds to the saturation pressure of ammonia at a temperature of 50°F . During the mission, ammonia will be removed from the tank, and some of the liquid ammonia will evaporate to keep the larger vapor space filled. During the ground time between filling the tank and starting the mission, the liquid ammonia will slowly expand as the temperature increases. Under the 87.5-percent fill condition, this expansion is such that no ammonia vaporization

will occur for temperatures lower than 50°F. Since the 50°F ammonia temperature at the end of the mission has been established as the limiting factor, it is necessary to calculate the maximum temperature of the ammonia at the start of the mission. The amount of ammonia which will evaporate during the flight to keep the vapor space filled is as follows:

$$\frac{100 \text{ gal}}{7.48 \text{ gal/ft}^3} \times 0.3034 \text{ lb/ft}^3 = 4.06 \text{ lb.} \quad (2)$$

The 0.3034 pound per cubic foot is the density of ammonia vapor at 50 psig. The evaporation of 4.06 pounds of ammonia will absorb 2,310 Btu's of heat.

$$4.06 \text{ lb} \times 570 \text{ Btu/lb} = 2,310 \text{ Btu.} \quad (3)$$

The total heat input to the ammonia during a 1/2-hour mission with an ambient air temperature of 90°F is as follows:

$$\frac{kA \Delta T t}{L} = \frac{0.023 \times 33.45 \times 40 \times 0.5}{0.0835} = 185 \text{ Btu} \quad (4)$$

where

k is conductivity.

A is area.

ΔT is 90°F - 50°F = 40°F.

t is time.

L is insulation thickness.

As shown above, 2,310 Btu's will be absorbed by the evaporation of the 4.06 pounds of ammonia, and only 185 Btu's will be absorbed during the mission. Therefore, the ammonia will be cooler at the end of the mission. Theoretically, the mission could start at an ammonia temperature higher than 50°F, but the 75-psig working pressure which represents a 50°F ammonia temperature would be the controlling factor. Therefore, the mission must start at an ammonia temperature lower than 50°F.

Since it has been established that the aircraft tank will be filled with -28°F ammonia and that the ammonia temperature at takeoff cannot exceed 50°F without venting, the next question is the permissible length of time between refueling and takeoff. The maximum elapsed time from refueling to takeoff for no loss caused by vaporization (other than the 4.06 pounds required for tank pressurization) is calculated as follows:

$$t = \frac{W_F c_p (T_2 - T_1)}{q} = \frac{W_F c_p L (T_2 - T_1)}{kA \Delta T} \quad (5)$$

where

ΔT is ambient temperature minus average fuel temperature

$$= 90 - \left[-28 + \frac{50 - (-28)}{2} \right] = 79^{\circ}\text{F}. \quad (6)$$

T_1 = ammonia temperature at fill ($^{\circ}\text{F}$).

T_2 = ammonia temperature at takeoff ($^{\circ}\text{F}$).

c_p = average specific heat of liquid ammonia

$$= 1.06 + 1.13 = 1.1 \text{ Btu/lb } ^{\circ}\text{F}$$

W_F = fuel weight = 569 lb.

$$t = \frac{569 \times 1.1 \times .0835 \times 78}{0.23 \times 33.45 \times 79} = 67 \text{ hr}. \quad (7)$$

Therefore, the ammonia will reach a temperature of 50°F when stored at an ambient temperature of 90°F for 67 hours. For any shorter period of elapsed time between refueling and takeoff, the temperature of the fuel will be lower at time of takeoff, and will not reach 50°F during the assumed 1/2-hour mission. For any period of elapsed time between refueling and takeoff longer than those quoted above, evaporation of the ammonia will maintain the ammonia at 50°F , and the excess ammonia vapor will be vented to the atmosphere. The rate of venting or loss due to evaporation is calculated as follows:

For 90°F ambient conditions,

$$q \text{ input} = \frac{kA \Delta T}{L} = \frac{0.023 \times 33.45 \times 40}{0.0835} = 369 \text{ Btu/hr}. \quad (8)$$

$$\text{NH}_3 \text{ loss} = \frac{369 \text{ Btu/hr}}{570 \text{ Btu/lb}} = 0.647 \text{ lb/hr}. \quad (9)$$

ENGINE PERFORMANCE

An existing computer program for hydrocarbon-fuel engine cycle performance was modified to determine gas turbine performance using ammonia as a fuel. In order to expedite and complete this study in a timely manner, the following assumptions were made:

1. Stable combustion is obtainable when ammonia is used as a fuel.
2. Lower heating value of ammonia is selected as 8,000 Btu/lb.
3. Combustor performance of an ammonia-fueled engine is equal to that of a hydrocarbon-fueled engine.
4. Standard combustor fuel injection is used.

The lower heating value of ammonia (8,000 Btu/lb) will result in higher specific fuel consumption (SFC) than that experienced with hydrocarbon fuels (18,400 Btu/lb). This strongly suggests regeneration, particularly because fouling is not expected to present problems with the products of combustion received from ammonia fuels. These combustion products are water and nitrogen, with small traces of ammonium nitrate and nitrogen dioxide. According to available literature, these products of combustion are nontoxic and noncorrosive.

A 75-percent-effectiveness regenerator was selected for this study. The specific regenerator weight is estimated to be approximately 30 pounds per pound per second of airflow. For example, the T53 engine having an airflow of approximately 11 pounds per second will have an additional weight of 330 pounds.

Estimated engine performance curves for the T53-L-11 and T64-GE-10 are shown in Figures 14 and 15, respectively. The maximum rated power and the SFC at that power level (100-percent maximum rated power) are shown in the upper right-hand corner of each figure. As can be seen, the maximum power of each engine (nonregenerative) increased by approximately 15 percent when ammonia was used as a fuel, because, as ammonia has a much lower heating value than hydrocarbon fuels, which require an additional mass of ammonia to burn at the required turbine inlet temperature, the mass across the gasifier and power turbine will increase

by approximately 3 percent over the hydrocarbon-fueled engine. This 3-percent increase in mass flow will result in a 3-percent increase of output power. The remaining 12-percent increase in power is caused by the different properties of the products obtained from the combustion of the ammonia fuel; for example, a substantial increase in the ratio of specific heats.

When a 75-percent-effectiveness regenerator was applied to the ammonia-fueled T53 engine, the SFC of that engine was reduced by 29.8 percent at the maximum power condition. By applying a 75-percent-effectiveness regenerator to the ammonia-fueled T64, only a 7.7-percent reduction in SFC was realized. The smaller reduction in SFC in the T64 engine is caused by this engine's thermal cyclic characteristics; or more specifically, this engine has a compressor-pressure ratio of 12.57:1 as compared to a 6:1 compressor-pressure ratio for the T53 engine. As a general rule, regeneration would not be utilized on an engine having a compressor-pressure ratio higher than 8:1 with current turbine inlet temperatures (1,700-1,800°F). This is not to say that regenerators would not or should not be used on high-pressure-ratio engines. As turbine inlet temperature increases, the optimum pressure ratio for regeneration will increase accordingly. For example, in the case of an engine having a turbine inlet temperature of 2,000°F with a pressure ratio of 12:1 and a 75-percent-effectiveness regenerator, the SFC will decrease approximately 15 percent from the nonregenerative version. As shown above, the reduction in SFC with a turbine inlet temperature of 1,800°F was only 7.7 percent. In order to obtain a true comparison of hydrocarbon- and ammonia-fueled engines, the performance of a regenerative T53 engine utilizing hydrocarbon fuel (JP-4) was determined and is shown in Figure 14. The regenerative hydrocarbon-fueled engine showed a reduction of 28.1 percent in SFC from the nonregenerative engine at the maximum power level (100 percent). No attempt was made to determine the performance of a regenerative hydrocarbon-fueled T64 engine, because of only limited improvement in SFC, as discussed above.

UH-1D PERFORMANCE

The UH-1D helicopter is capable of hovering out of ground effect with a gross weight of 8,000 pounds at sea level pressure altitude and 60°F ambient temperature with normal rated power (900 horsepower). Therefore, the 8,000-pound gross weight condition was selected for this investigation. Figure 16 shows the power required at varying speeds at the selected gross weight. Helicopter mission analyses were conducted between the maximum endurance speed (61 knots) and maximum speed and best range (102 knots).

Using the engine performance shown in Figure 14 and the power required shown in Figure 16, the specific range for each craft was derived and is shown in Figure 17.

Typical payload-radius curves are shown in Figures 18 and 19. Data presented in Figure 18 were based on the high-pressure ammonia tank design, while Figure 19 data were derived using the low-pressure tank design. Table IV shows values extracted from Figures 17, 18, and 19 at a cruise speed of 102 knots and at a zero-payload condition. This condition represents a payload of a pilot, and the remaining weight is fuel and fuel tank. As shown in Figure 18, the internal fuel capacity of the UH-1D is 1,430 pounds. By incorporating external fuel tanks into the hydrocarbon-fueled configurations, the maximum range at zero payload can be determined. Note: All helicopter performance will be compared with performance of the nonregenerative hydrocarbon-fueled (JP-4) configurations. Specific range values (nautical miles per pound of fuel) shown in Table IV indicate that the nonregenerative hydrocarbon-fueled helicopter has an increased capability of 58 percent over the nonregenerative ammonia-fueled helicopter and one of 34 percent over the regenerative ammonia-fueled configuration, while the regenerative hydrocarbon-fueled helicopter has an increased capability of 45 percent over the nonregenerative version.

Utilizing the high-pressure ammonia tank design data shown in Table IV, the nonregenerative ammonia-fueled helicopter's mission radius capability was determined to be only one-fourth that of the nonregenerative hydrocarbon-fueled version, the capability of the regenerative ammonia configuration was slightly over one-third that of the nonregenerative hydrocarbon craft's capability, and the regenerative hydrocarbon-fueled helicopter had an increased capability of 35 percent over the nonregenerative version. By utilizing the low-pressure tank design, it was found that the regenerative ammonia-fueled helicopter's radius capability was approximately one-half that of the nonregenerative hydrocarbon-fueled craft. The ammonia-fueled nonregenerative helicopter with the low-pressure tanks had an increase of 29 percent in radius capability over the high-pressure tank version, while the regenerative configurations experienced an increase of 26 percent. From Figure 20, zero-payload and 1,750-pound-payload conditions were selected for comparison and are shown in Table V at a cruise speed of 61 knots, which is the speed for maximum endurance. The ammonia-fueled helicopter's endurance capability was about one-fourth that of the hydrocarbon-fueled craft.

Utilizing information depicted in Figures 21, 22, and 23, a comparison of helicopter productivity is shown in Table VI at mission radii of 20 and 40 nautical miles. Productivity data presented in Table VI indicate that the nonregenerative ammonia-fueled helicopter's productivity, depending upon

the mission radius, ranged from one-fourth to one-sixth that of the hydrocarbon-fueled craft's capability, while the regenerative ammonia-fueled craft's productivity ranged from one-third to one-fourth that of the nonregenerative hydrocarbon-fueled craft's capability.

A quick survey of the fuel requirements for conducting a 40-nautical-mile-radius mission as shown in Table VI indicates that the nonregenerative ammonia-fueled helicopter would require 1.15 pounds of ammonia per pound of cargo transferred, or six times as much as fuel as that required by the standard UH-1D. The regenerative ammonia-fueled version will require over twice as much fuel as the standard UH-1D, while the regenerative hydrocarbon-fueled helicopter will require only about half as much fuel as the standard UH-1D. Figure 24 indicates that missions longer than a 40-nautical-mile radius for the nonregenerative ammonia-fueled helicopter and longer than a 60-nautical-mile radius for the regenerative configuration would not be practical when transferring cargo.

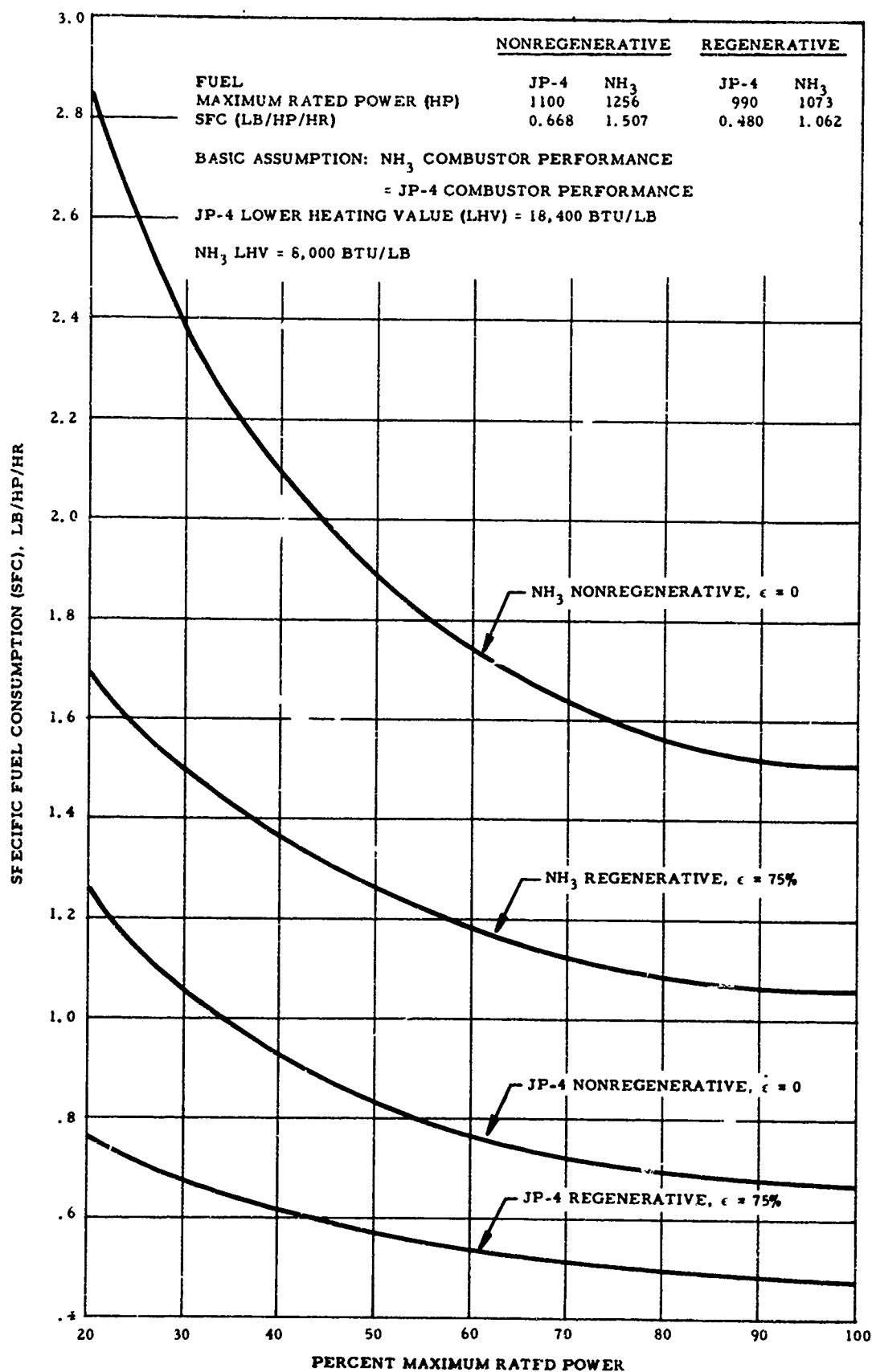


Figure 14. Estimated Engine Performance Utilizing Ammonia as a Fuel, T53-L-11.

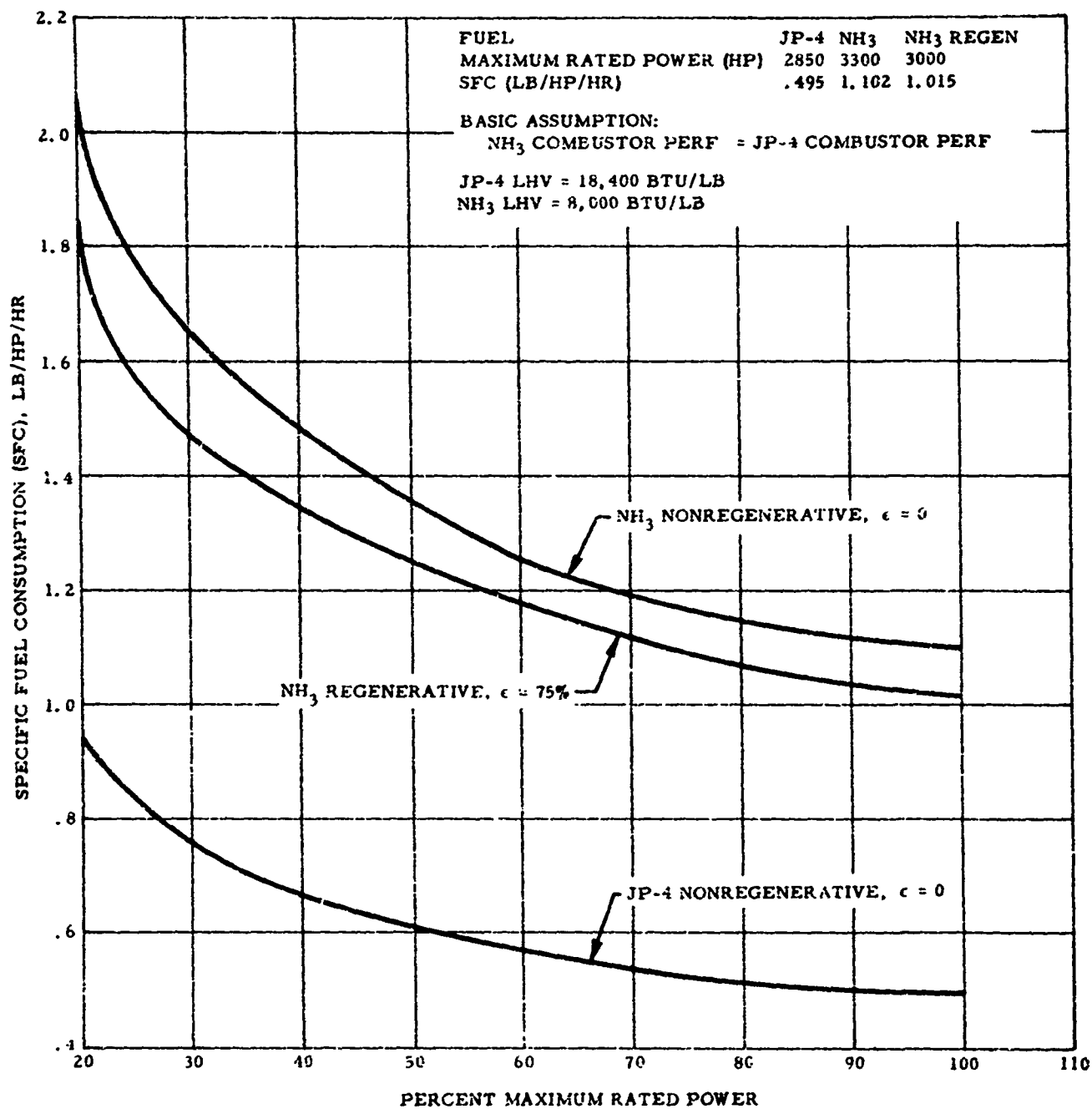


Figure 15. Estimated Engine Performance Utilizing Ammonia as a Fuel, T64-GE-10.

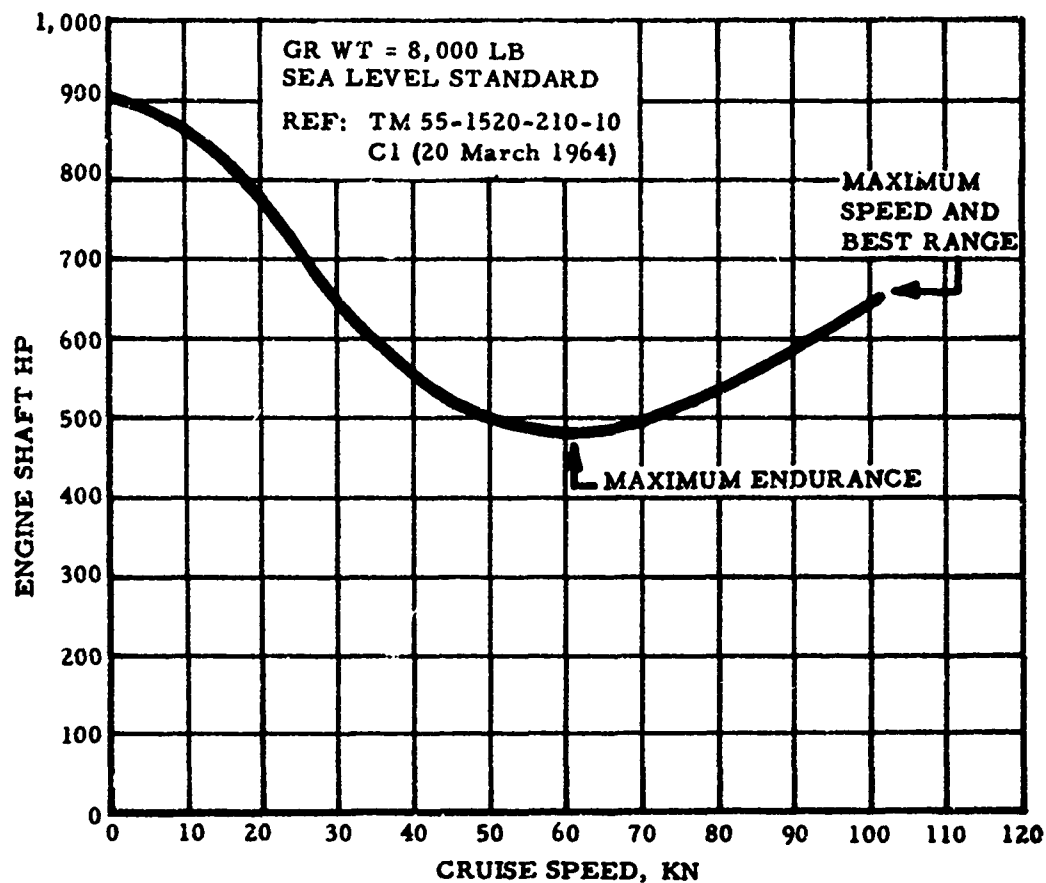


Figure 16. UH-1D, Cruise Speed Versus Engine Shaft Horsepower.

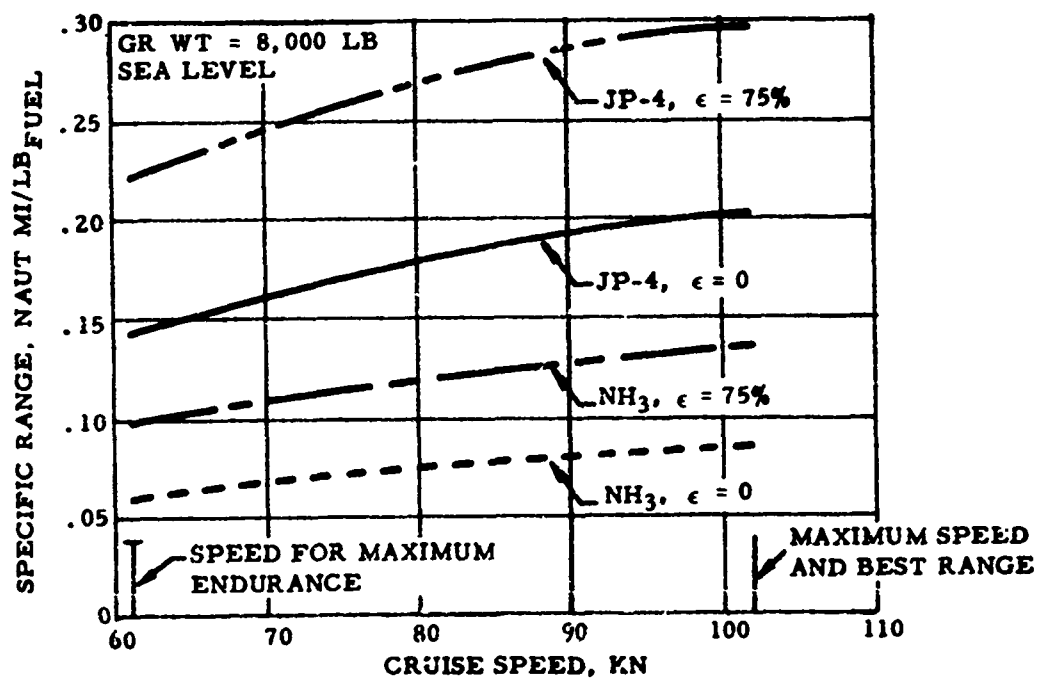


Figure 17. UH-1D, Cruise Speed Versus Specific Range.

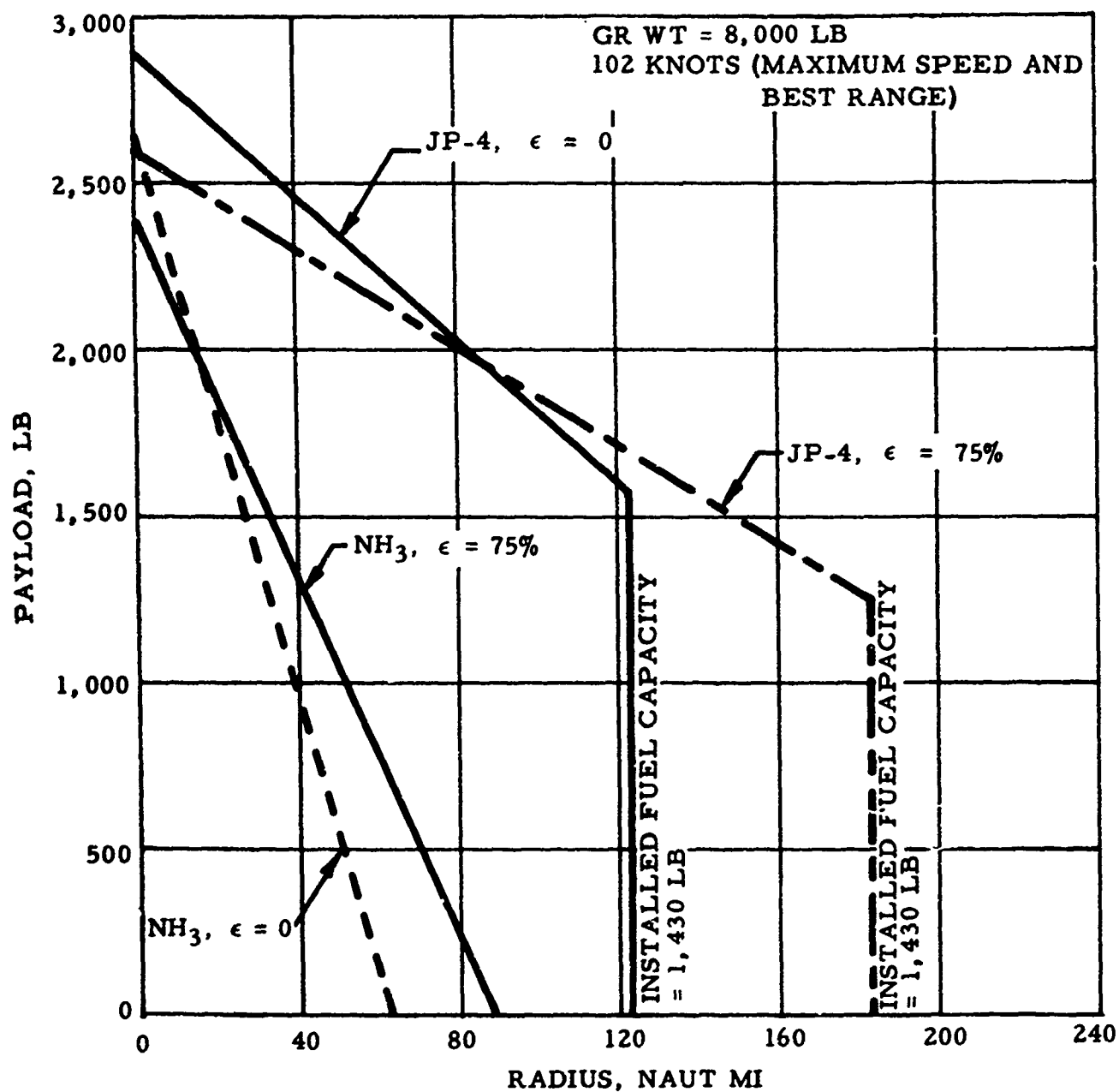


Figure 18. UH-1D, Radius Versus Payload, 500-PSIG Fuel Tank, NH₃.

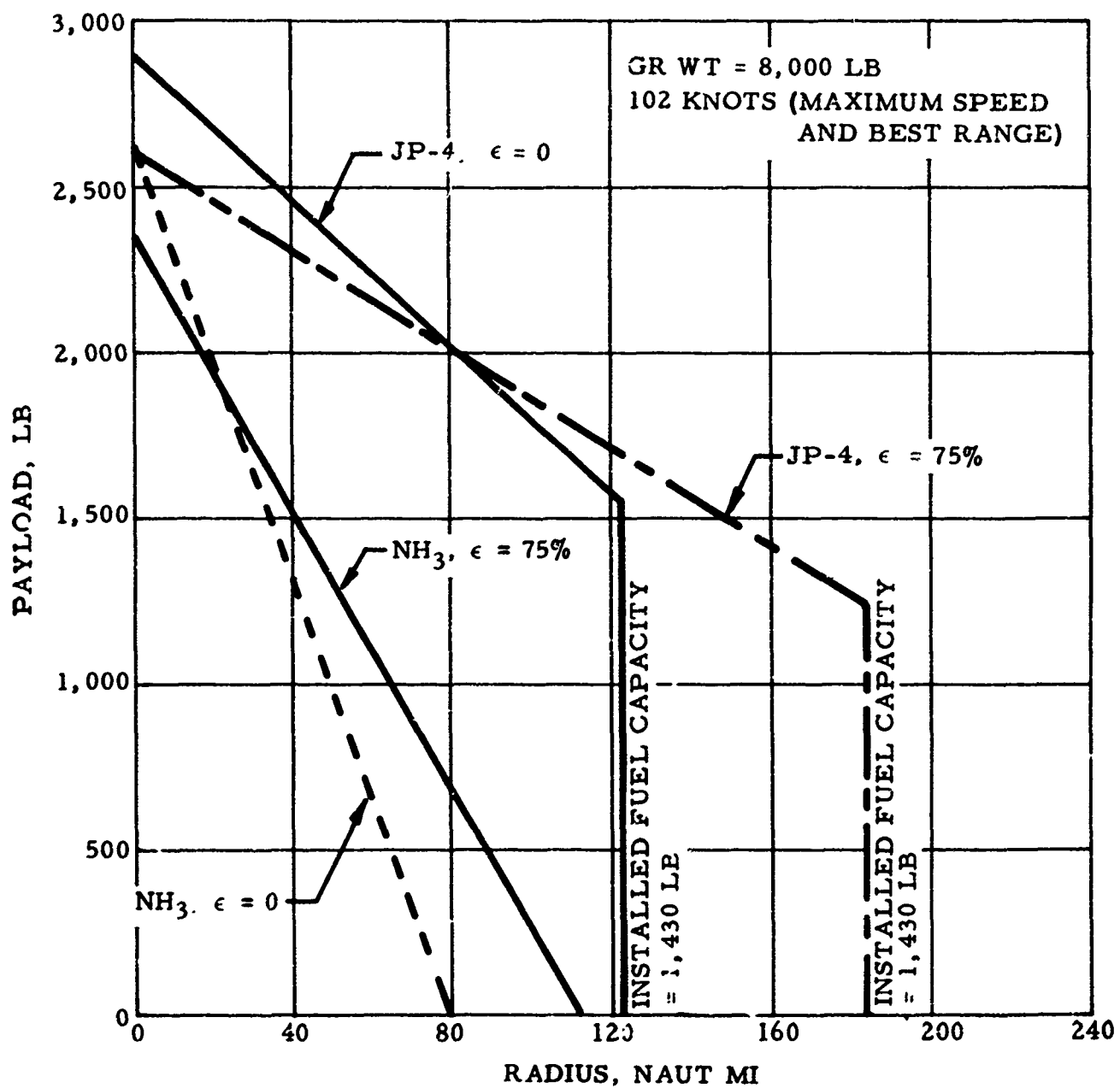


Figure 19. UH-1D, Radius Versus Payload, 75-PSIG Fuel Tank, NH₃.

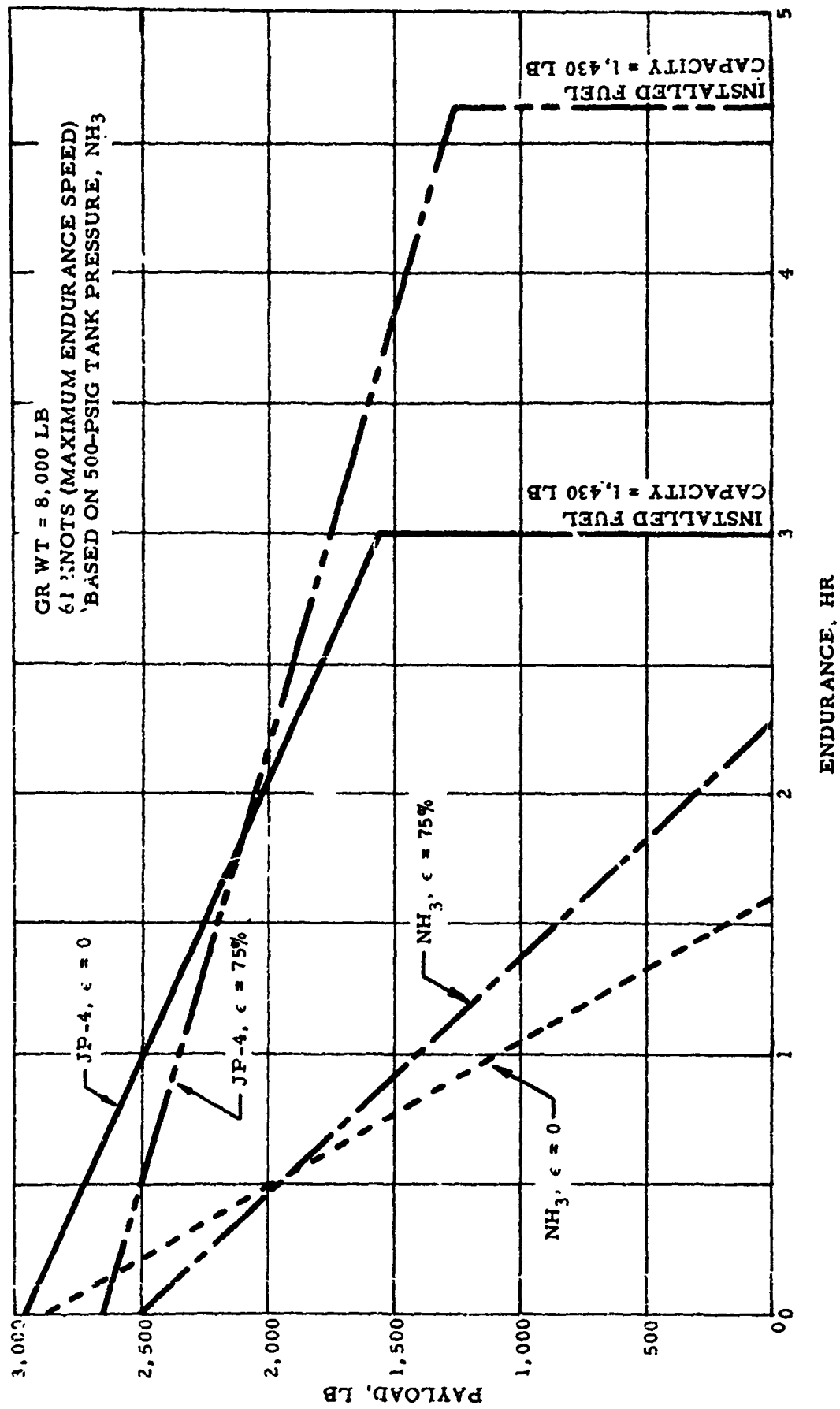


Figure 20. UH-1D, Endurance Versus Payload.

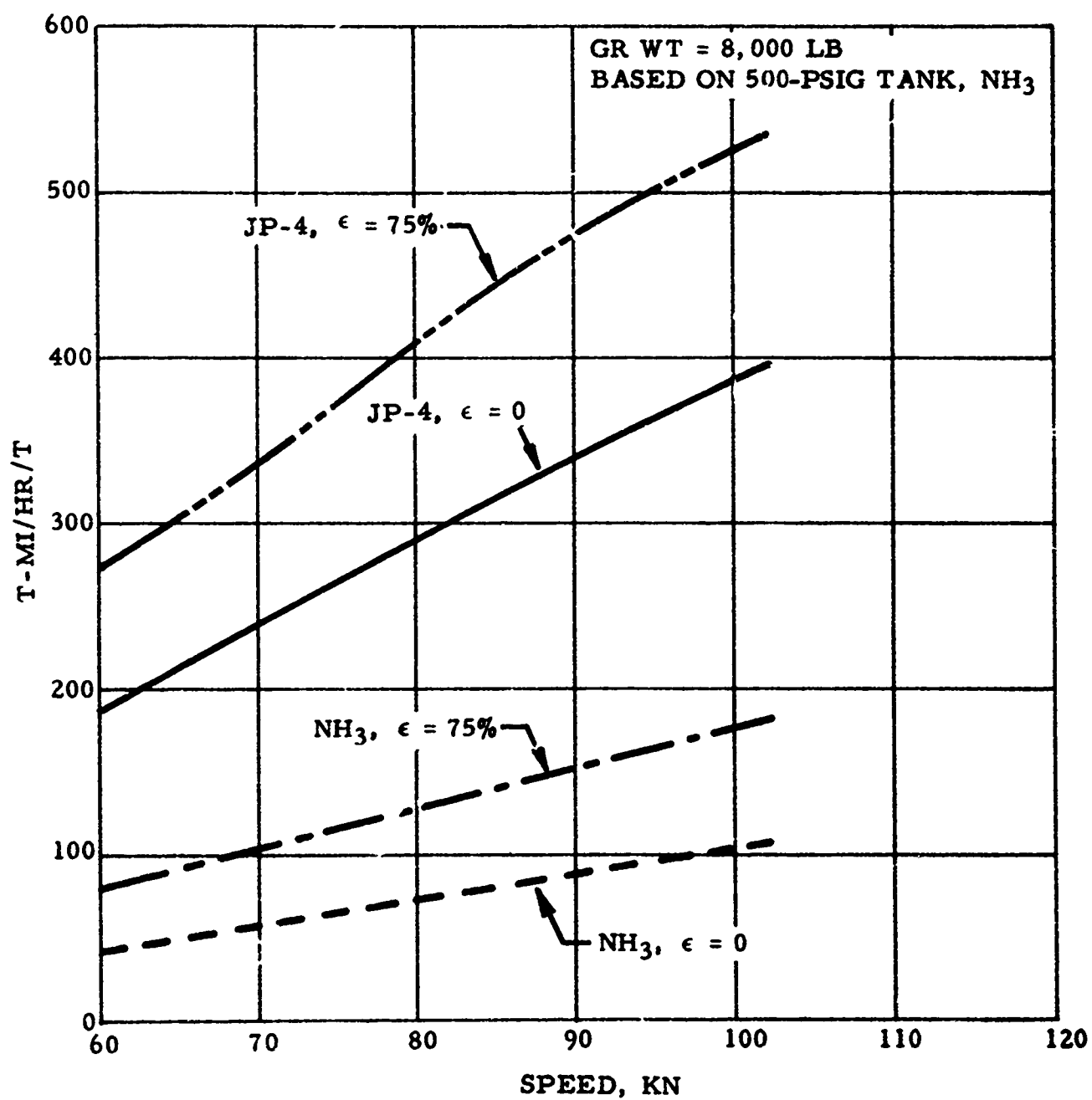


Figure 21. UH-1D, Speed Versus Ton-Miles/Hour/Ton,
Radius = 20 Nautical Miles.

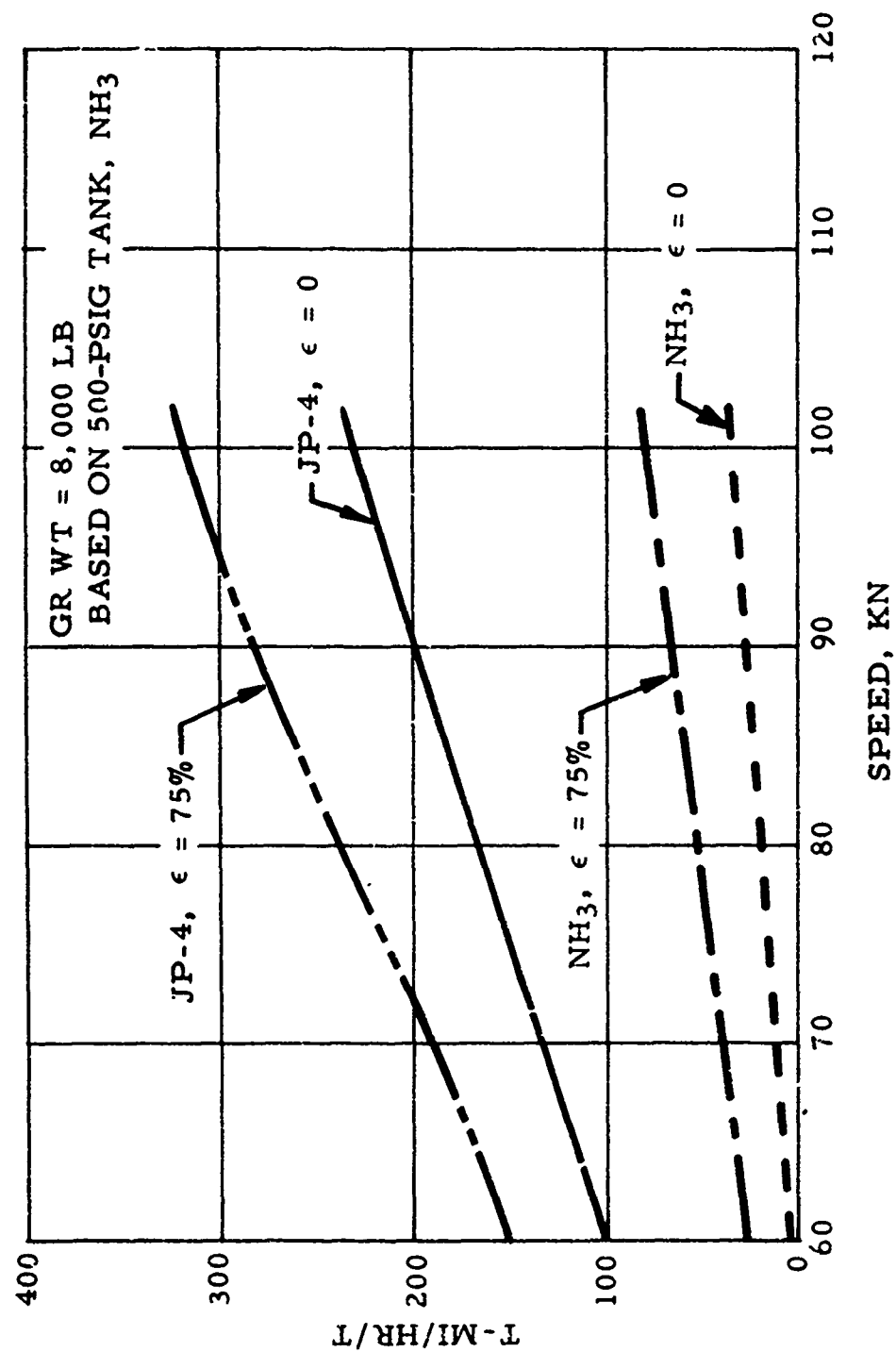


Figure 22. UH-1D, Speed Versus Ton-Miles/Hour/Ton,
Radius = 40 Nautical Miles.

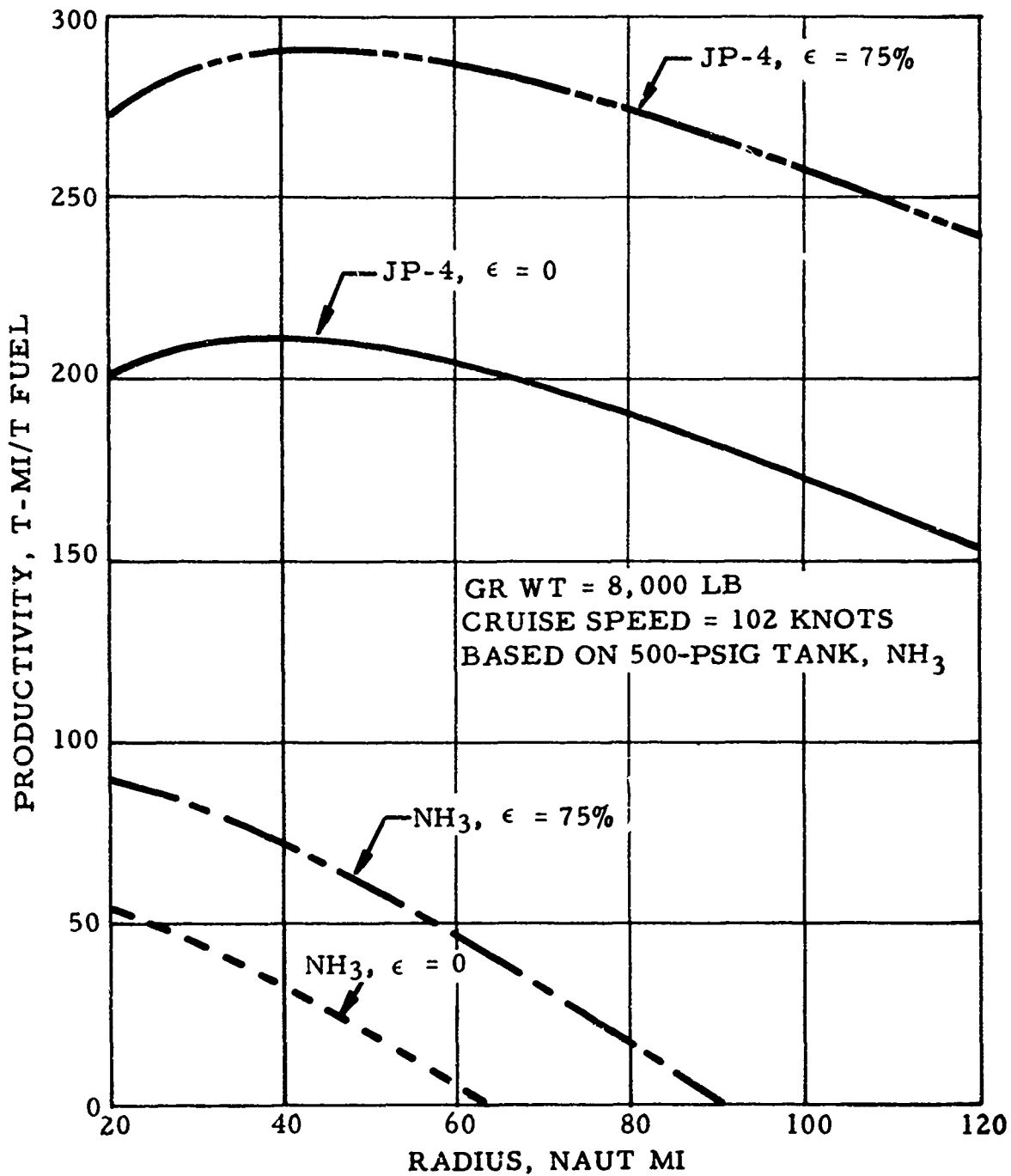


Figure 23. UH-1D, Radius Versus Productivity.

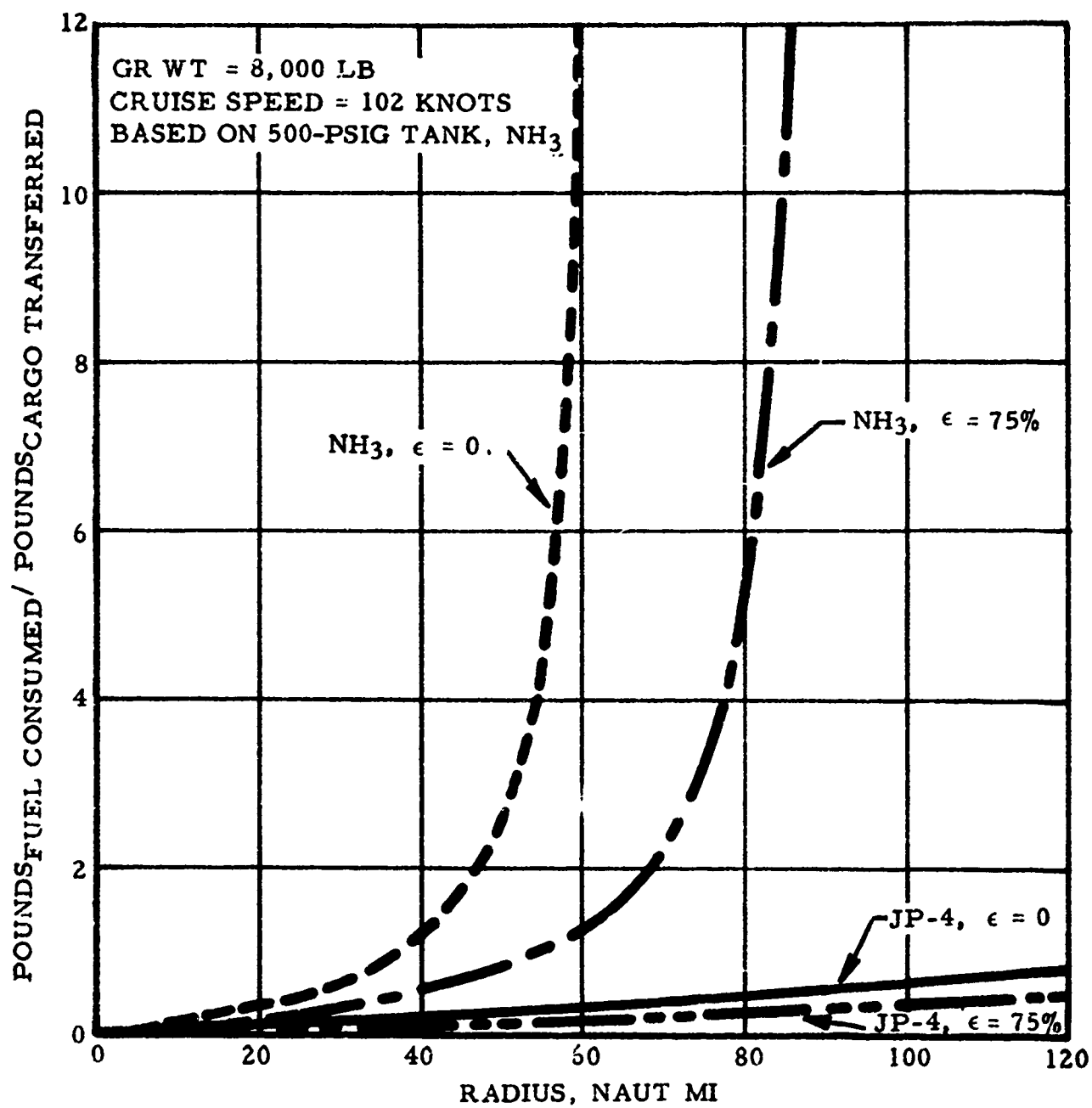


Figure 24. UH-1D, Radius Versus $\frac{\text{Pounds Fuel Consumed}}{\text{Pounds Cargo Transferred}}$.

TABLE IV UH-1D, PAYLOAD VERSUS RADIUS CAPABILITY, GROSS WEIGHT = 8,000 POUNDS						
Configuration	Tank		Speed (kn)	Payload (lb)	Radius (naut mi)	Specific Range (naut mi /lb)
	Pressure NH ₃	Endurance (hr)				
JP-4 $\epsilon = 0$	-	102	0	240		.220
JP-4 $\epsilon = 75\%$	-	102	0	325		.295
NH ₃ $\epsilon = 0$	High	102	0	62		.083
NH ₃ $\epsilon = 75\%$	High	102	0	89		.135
NH ₃ $\epsilon = 0$	Low	102	0	80		.083
NH ₃ $\epsilon = 75\%$	Low	102	0	112		.135

References: Figures 17, 18, and 20.

TABLE V UH-1D, ENDURANCE, GROSS WEIGHT = 8,000 POUNDS						
Configuration	Tank		Speed (kn)	Payload (lb)	Endurance (hr)	Specific Range (naut mi /lb)
	Pressure NH ₃	Endurance (hr)				
JP-4 $\epsilon = 0$	-	61	1750	2.60		0.143
JP-4 $\epsilon = 75\%$	-	61	1750	3.00		0.223
NH ₃ $\epsilon = 0$	High	61	1750	0.65		0.060
NH ₃ $\epsilon = 75\%$	High	61	1750	0.70		0.098
JP-4 $\epsilon = 0$	-	61	0	6.0		0.143
JP-4 $\epsilon = 75\%$	-	61	0	8.0		0.223
NH ₃ $\epsilon = 0$	High	61	0	1.6		0.060
NH ₃ $\epsilon = 75\%$	High	61	0	2.3		0.098

Reference: Figure 20.

TABLE VI UH-1D, PRODUCTIVITY, GROSS WEIGHT = 8,000 POUNDS									
Configuration	Tank		Speed (kn)	Payload (lb)	Radius (naut mi.)	T - Mi Hr - T	T - Mi T	Lb Fuel Lb Cargo	Specific Range (naut mi /lb)
	Pressure NH ₃	Endurance (hr)							
JP-4 $\epsilon = 0$	-	102	2680	20	394	-	-	-	0.222
JP-4 $\epsilon = 75\%$	-	102	2470	20	533	-	-	-	0.295
NH ₃ $\epsilon = 0$	High	102	1800	20	106	-	-	-	0.083
NH ₃ $\epsilon = 75\%$	High	102	1875	20	181	-	-	-	0.135
JP-4 $\epsilon = 0$	-	102	2470	40	235	212	0.19	0.222	0.222
JP-4 $\epsilon = 75\%$	-	102	2310	40	322	290	0.11	0.295	0.295
NH ₃ $\epsilon = 0$	High	102	980	40	37	33	1.15	0.083	0.083
NH ₃ $\epsilon = 75\%$	High	102	1310	40	82	72	0.50	0.135	0.135

References: Figures 18, 21, 22, 23, and 24.

CV-7A PERFORMANCE

The CV-7A aircraft, which is powered by two T64-GE-10 gas turbine engines, has two gross weight ratings, the lighter rating of 34,000 pounds depicting the aircraft in its STOL configuration and the heavier gross weight rating of 38,000 pounds depicting the aircraft in a conventional configuration. For the purpose of this study, a gross weight of 38,000 pounds was utilized, of which 22,530 pounds represents the aircraft empty weight, therefore leaving a useful load of 15,470 pounds. This aircraft has an internal hydrocarbon-fuel capacity of 13,556 pounds.

Actual aircraft characteristics, such as weights, speed versus power required, etc., were not available at the time of this investigation. Therefore, data pertaining to the aircraft characteristics were gathered from early proposals by The de Havilland Aircraft of Canada Ltd.'s model specifications, and from the AVCOM CV-7A Project Manager's office. Using the engine performance shown in Figure 15 and the power required shown in Figure 25, the specific range was derived for each engine configuration (JP-4 $\epsilon = 0$, NH₃ $\epsilon = 0$, NH₃ $\epsilon = 75$ percent) and is shown in Figure 26.

Typical payload-radius curves were derived based on the high-pressure ammonia-tank design at cruise speeds of 120, 160, and 200 knots, and are shown in Figures 27, 28, and 29, respectively. Using the low-pressure tank design, payload-radius curves at cruise speeds of 160 and 200 knots were determined and are shown in Figures 30 and 31, respectively. As seen from the curves, there is no advantage in the regenerative ammonia-fueled aircraft, because of the T64 thermal cycle characteristics as discussed in the engine performance studies section of this report. The maximum radius capability of the hydrocarbon-fueled CV-7A was reduced by approximately 70 percent when the ammonia fuel was considered in conjunction with the high-pressure tank design. Using the low-pressure tank design, a 62-percent reduction was realized.

Aircraft productivity curves in ton-miles per hour per ton of fuel are shown in Figures 32 and 33, and in Figure 34, which also shows aircraft productivity in ton-miles per ton of fuel. In general, the productivity of the ammonia-fueled craft is about one-fourth that of the hydrocarbon-fueled craft's capability. The low-pressure tank design has an increased productivity capability of approximately 35 percent over the high-pressure tank design. Figure 35 gives a brief survey of the fuel logistics; that is, pounds of fuel consumed per pound of cargo transferred at a cruise speed of 160 knots, which is the speed for maximum range. For example, in the case of a mission radius of 100 nautical miles and the transfer of 10,000 pounds of cargo, the fuel requirements would be as follows:

<u>Aircraft Configuration</u>	<u>Fuel Required, Lb</u>
JP-4 $\epsilon = 0$	1,500
NH ₃ $\epsilon = 0$ and $\epsilon = 75\%$ with 75-psig tank pressure	6,100
NH ₃ $\epsilon = 0$ and $\epsilon = 75\%$ with 500-psig tank pressure	8,200

These curves indicate that missions having a radius greater than 120 nautical miles would not be practical for the ammonia-fueled fixed-wing craft when transferring cargo.

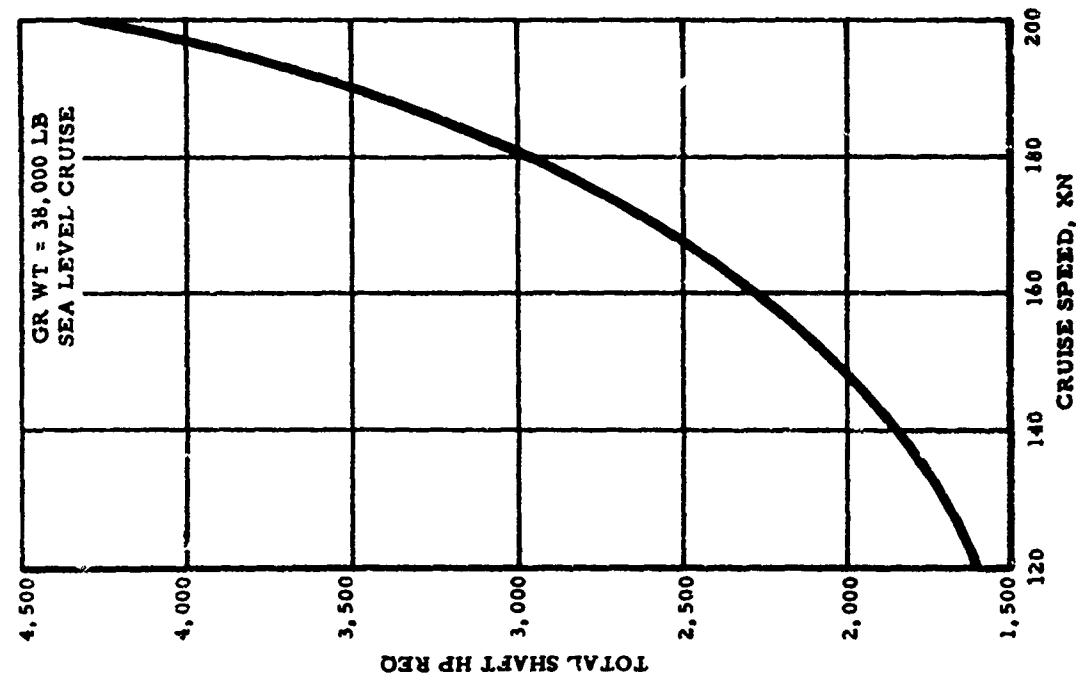


Figure 25. CV-7A, Cruise Speed Versus Total Shaft Horsepower Required.

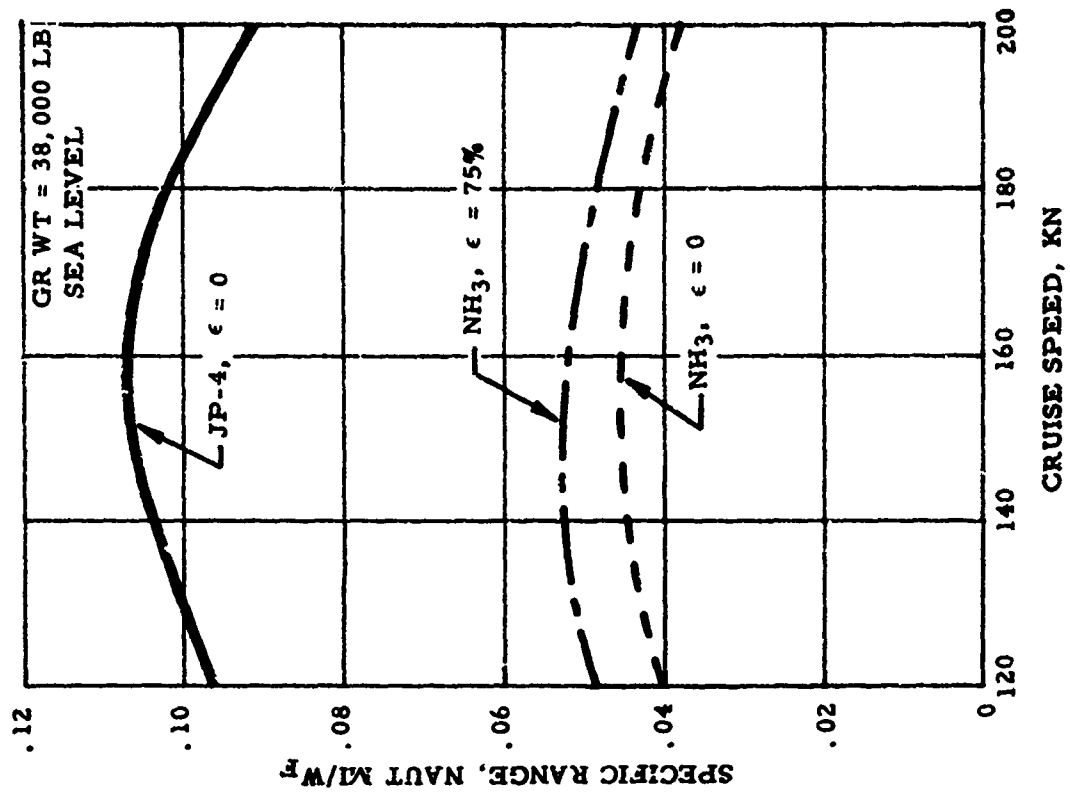


Figure 26. CV-7A, Cruise Speed Versus Specific Range.

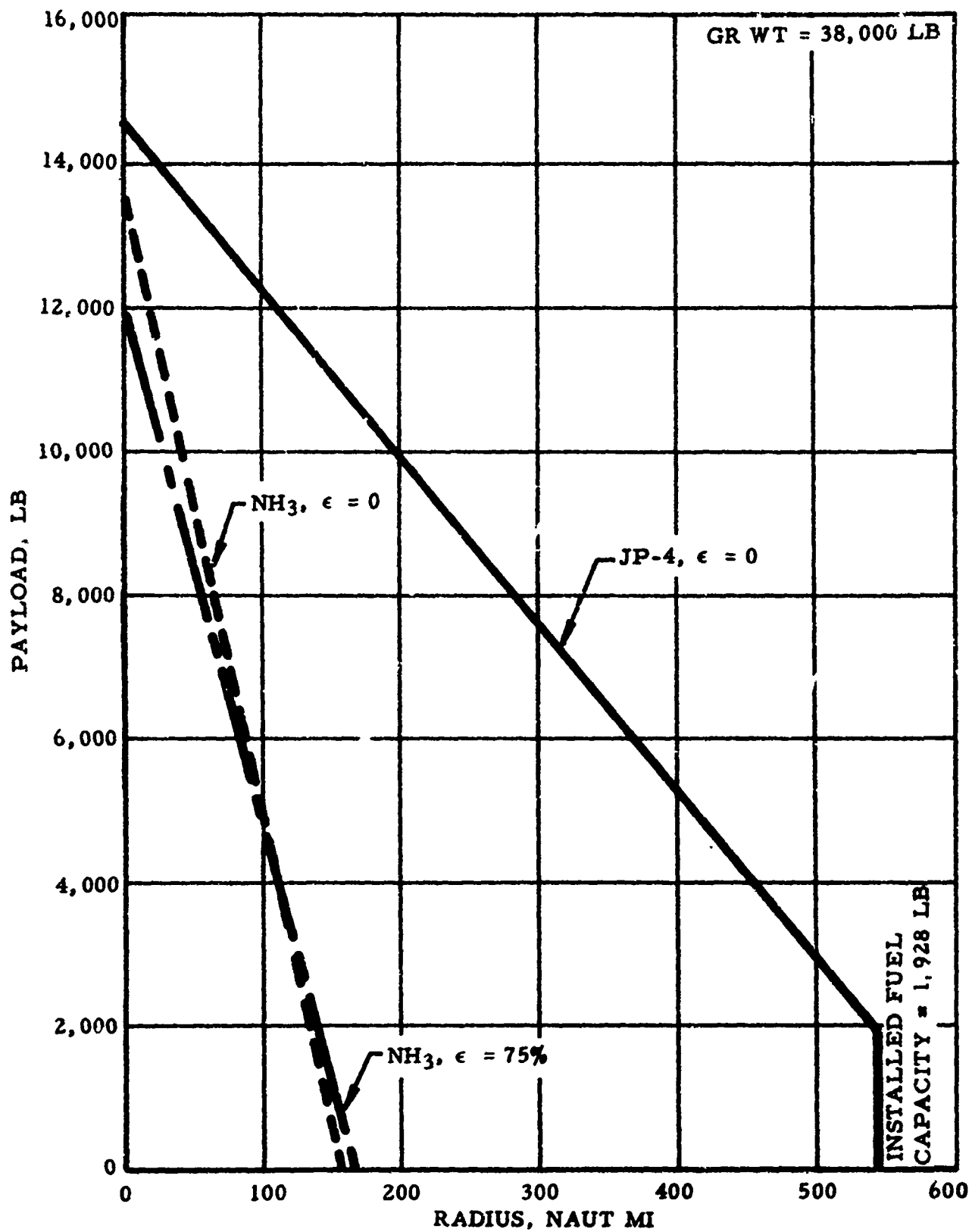


Figure 27. CV-7A, Radius Versus Payload, 120 Knots, 500 PSIG.

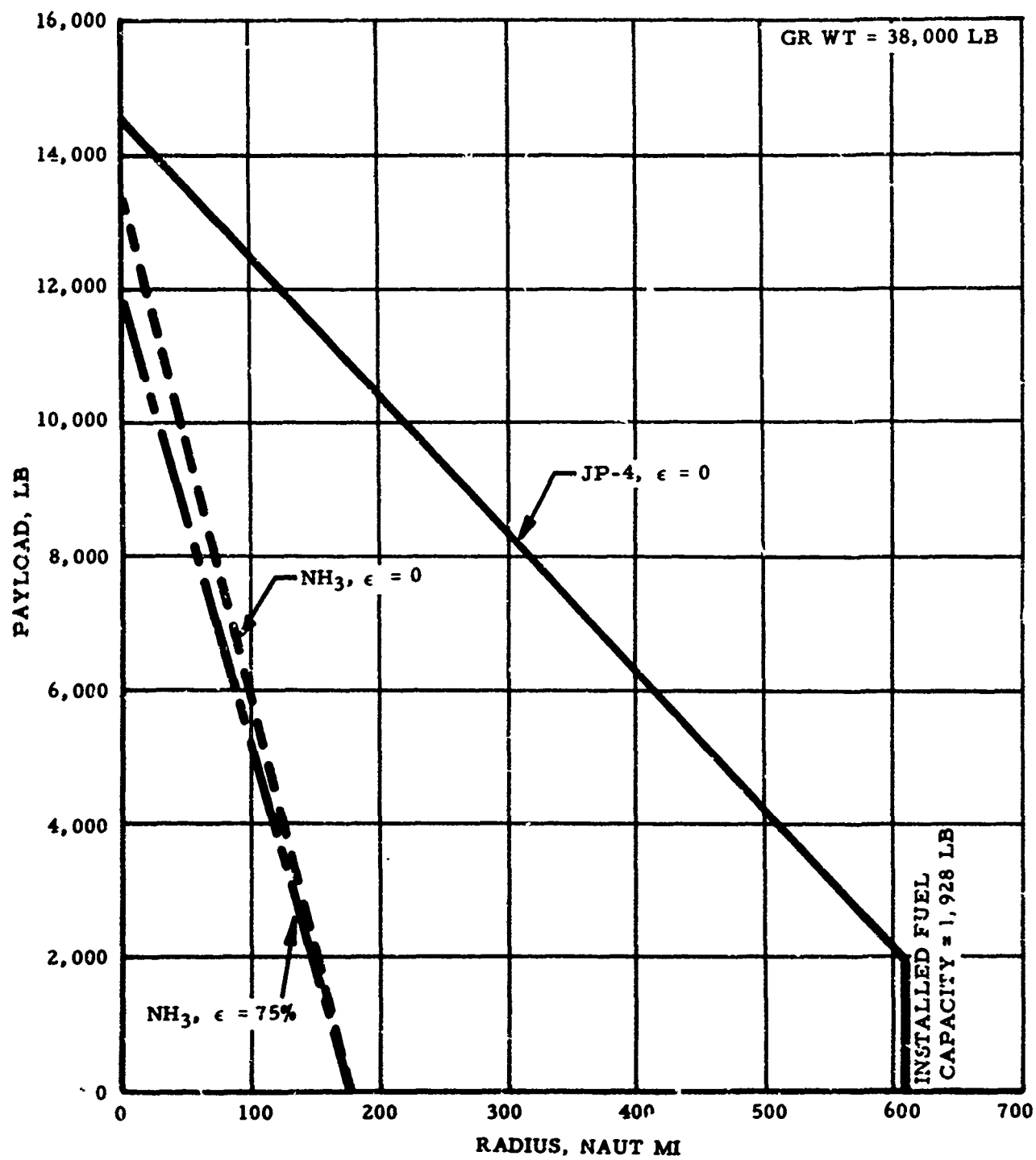


Figure 28. CV-7A, Radius Versus Payload, 160 Knots, 500 PSIG.

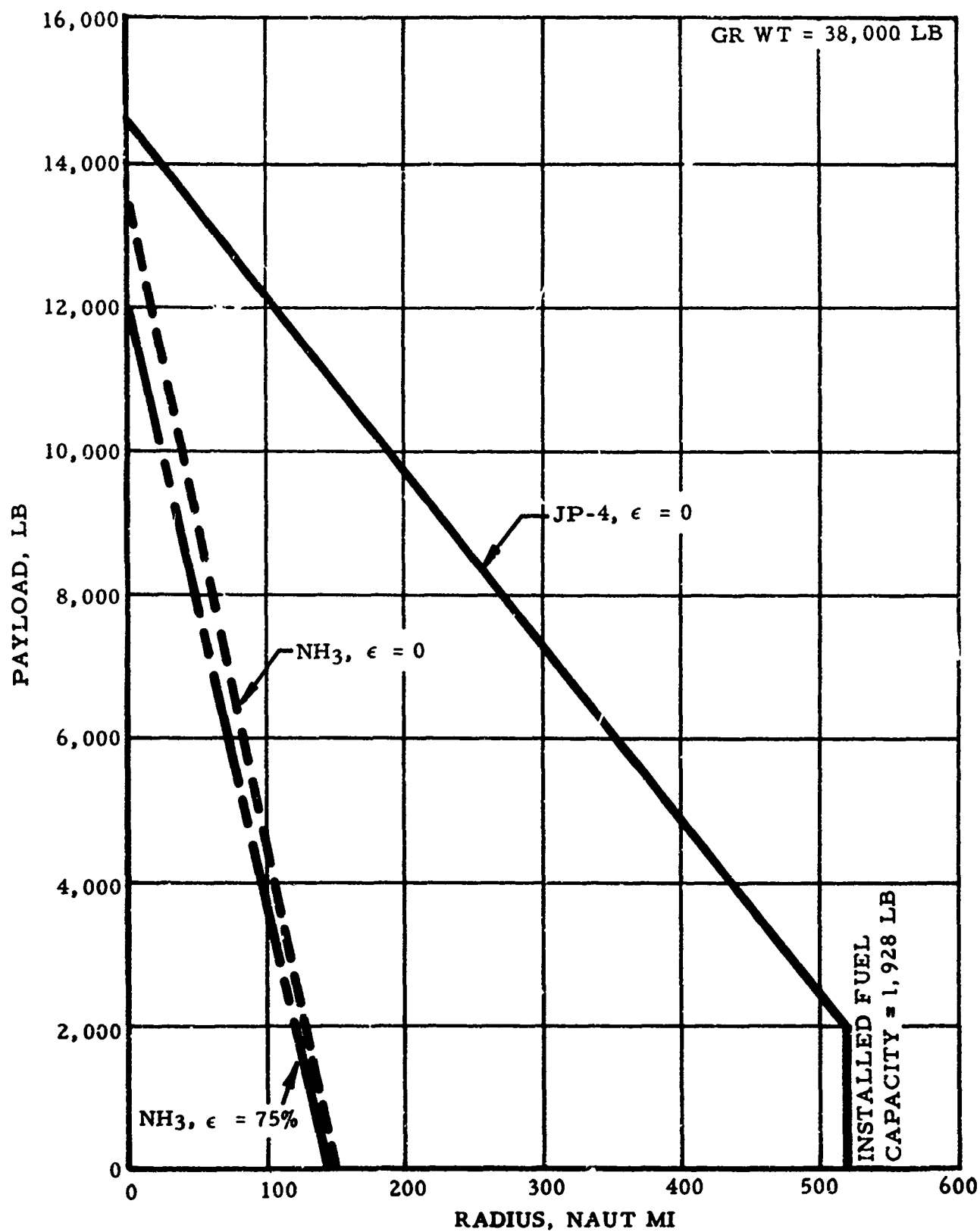


Figure 29. CV-7A, Radius Versus Payload, 200 Knots, 500 PSIG.

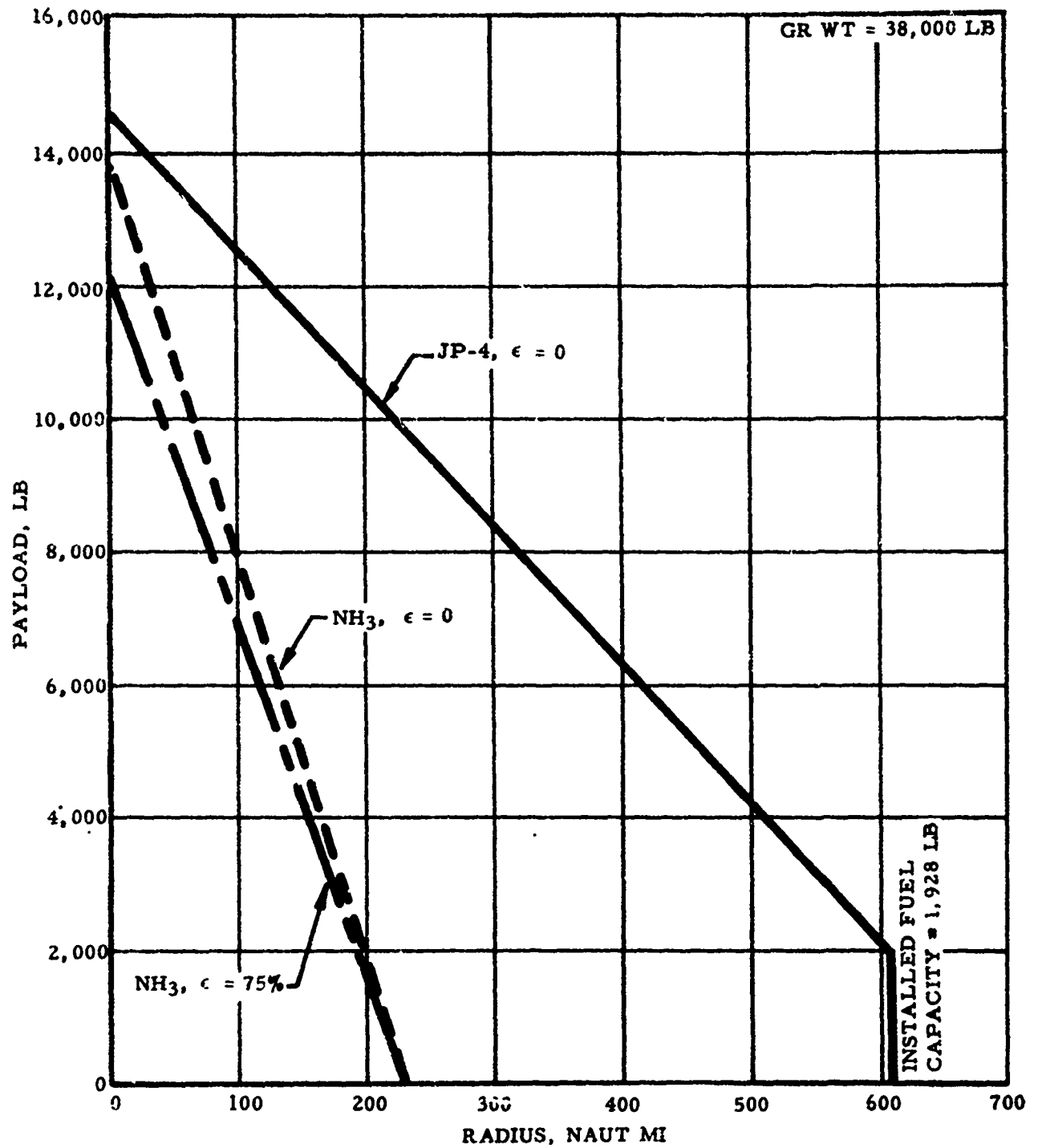


Figure 30. CV-7A, Radius Versus Payload, 160 Knots, 75 PSIG.

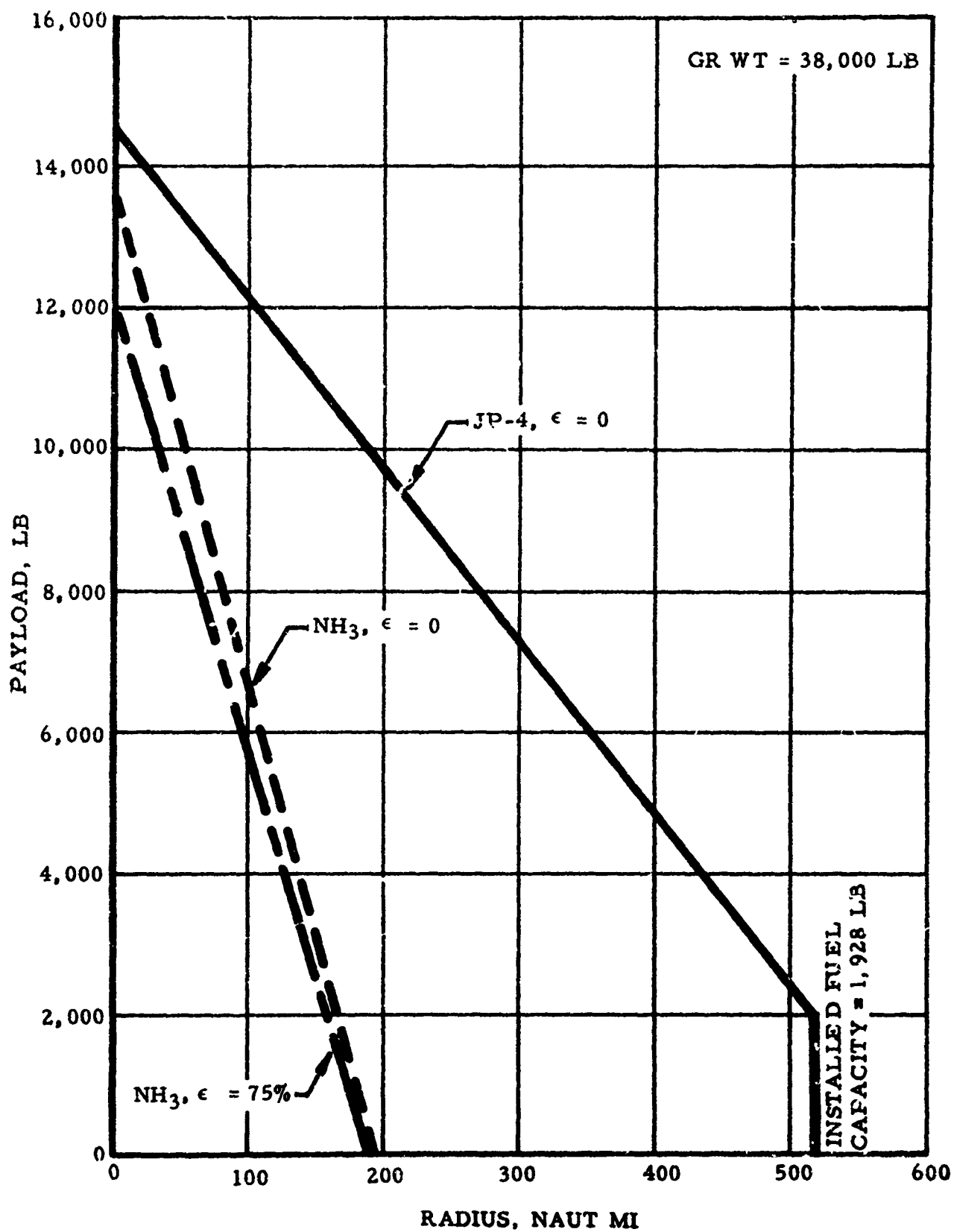


Figure 31. CV-7A, Radius Versus Payload, 200 Knots, 75 PSIG.

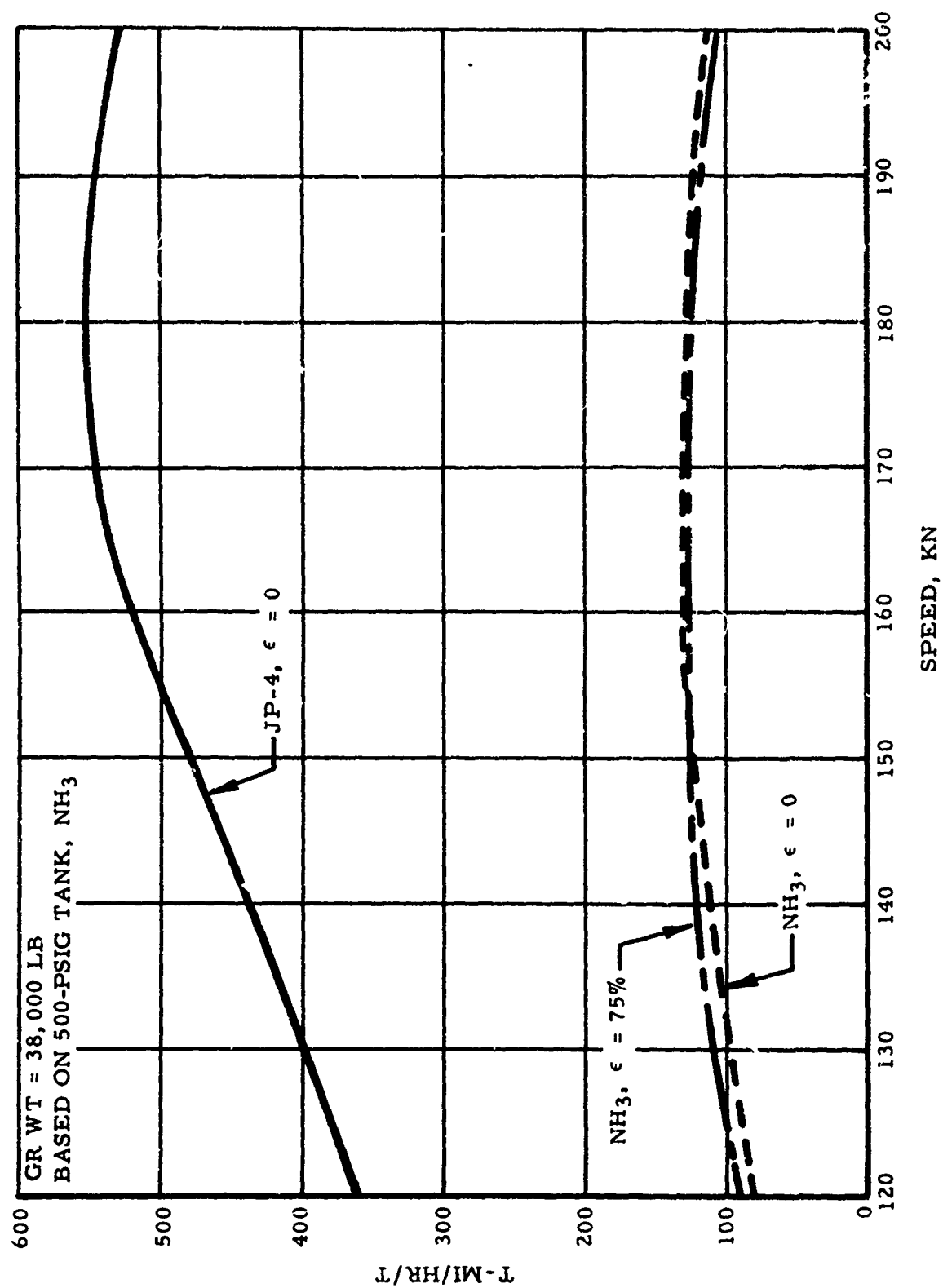


Figure 32. CV-7A, Speed Versus Ton-Miles/Hour/Ton,
Radius = 80 Nautical Miles.

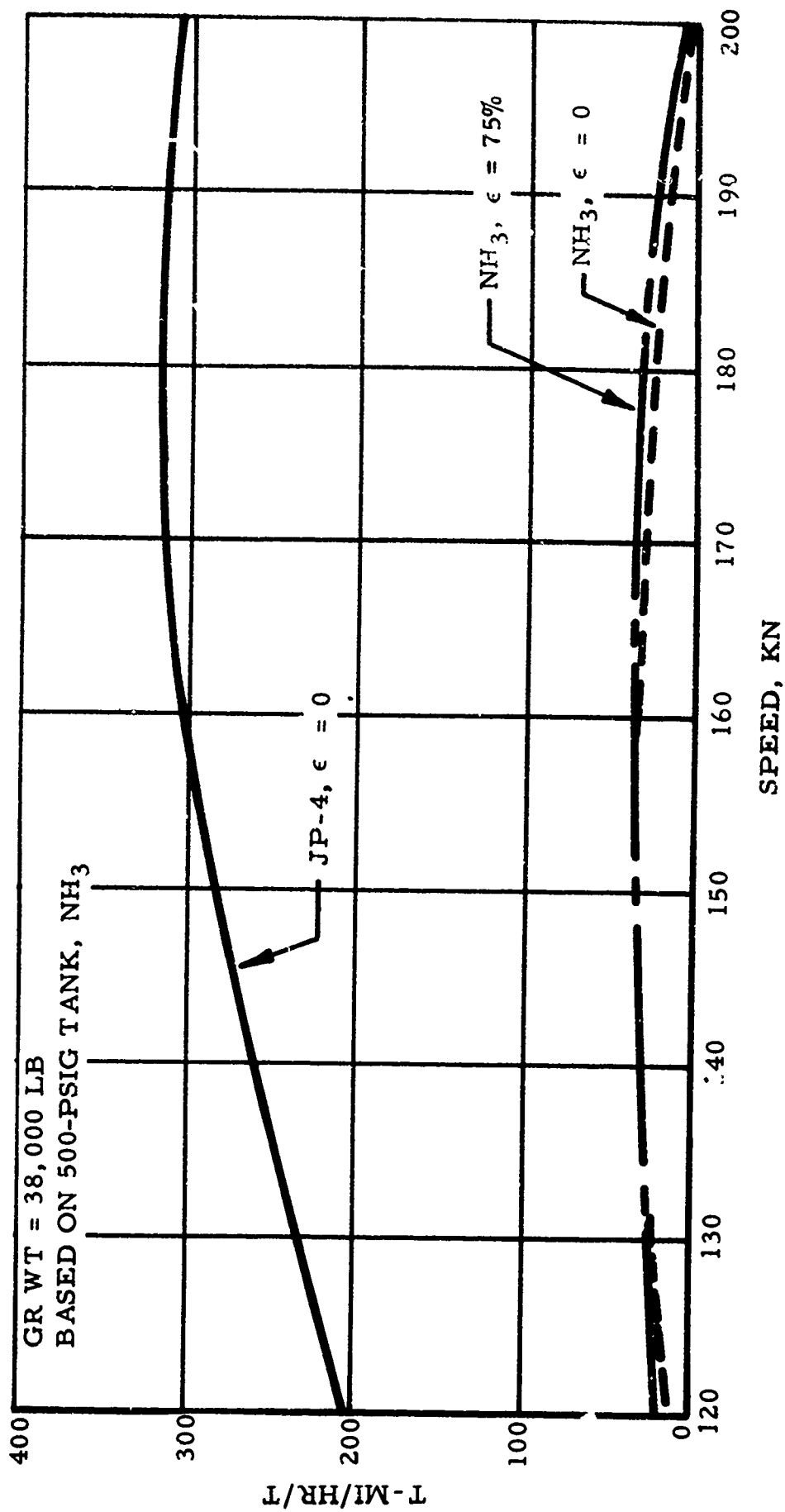


Figure 33. CV-7A, Speed Versus Ton-Miles/Hour/Ton,
Radius = 140 Nautical Miles.

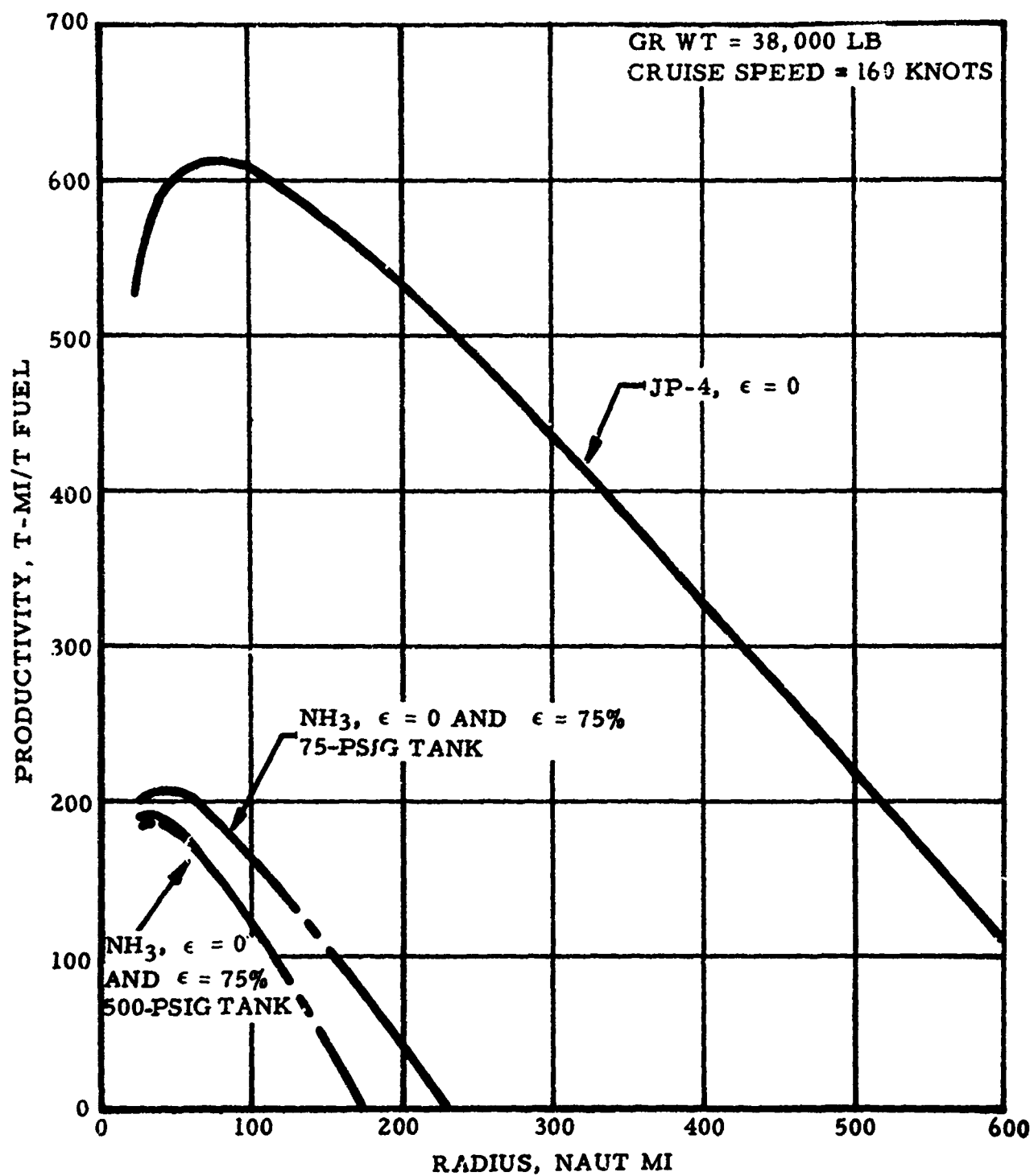


Figure 34. CV-7A, Radius Versus Productivity.

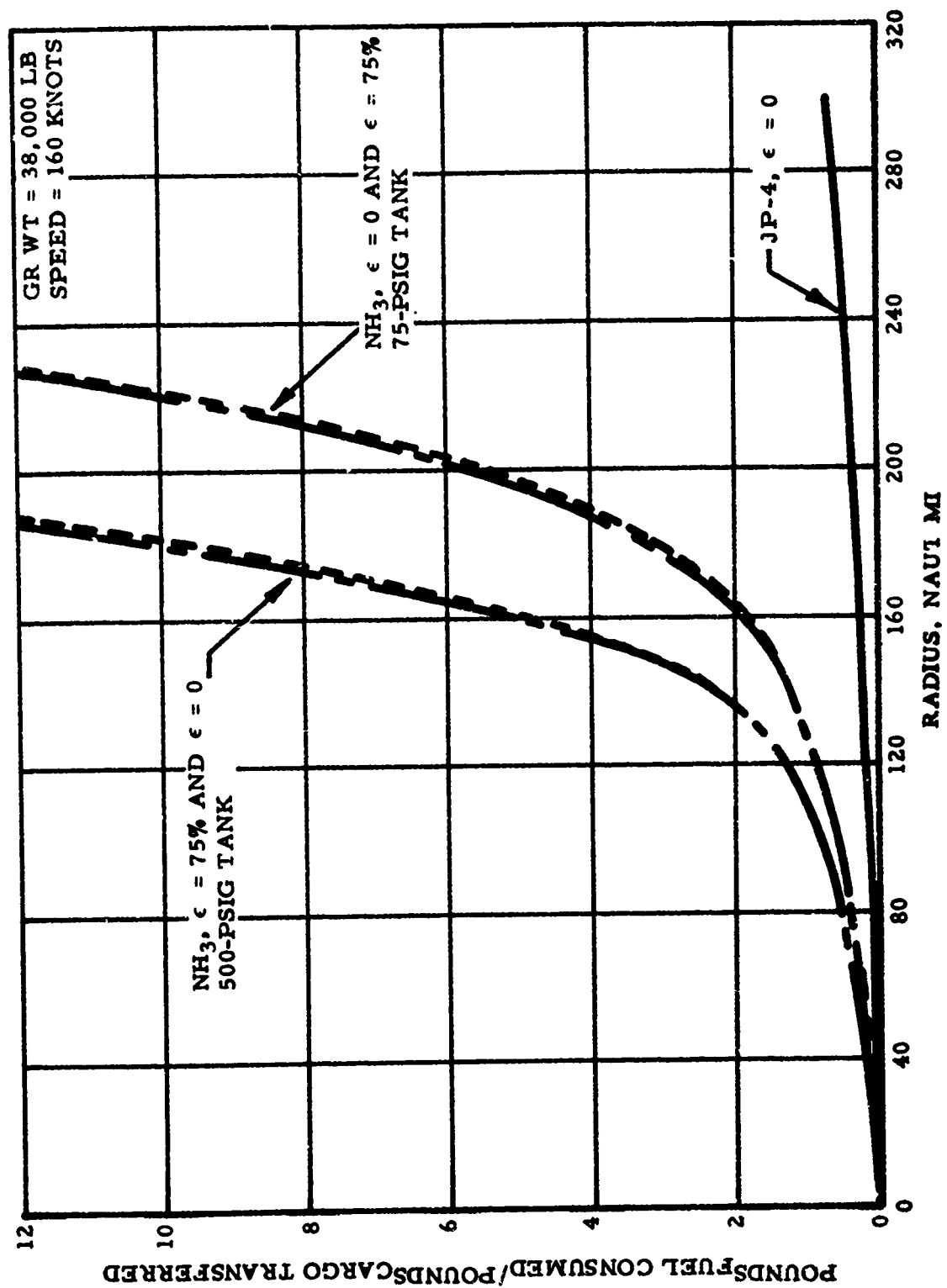


Figure 35. CV-7A, Radius Versus $\frac{\text{Pounds Fuel Consumed}}{\text{Pounds Cargo Transferred}}$.

ENGINE MAINTENANCE

Assuming that suitable materials and coatings will be developed and utilized in ammonia-fueled gas turbine engines and that the basic mission requirements of the aircraft remain the same, it can reasonably be stated that the maintenance requirements of ammonia-fueled engines should be basically the same as those for current hydrocarbon-fueled engines, although additional complexity is anticipated in the engine fuel controls and aircraft fuel systems. It should be noted that in case of ammonia spillage during refill of tanks, protective measures should be taken to keep the ammonia from contacting any aluminum surfaces.

ENGINE CONVERSION AND PRODUCTION COSTS

Using the report prepared for the U. S. Army Engineer Research and Development Laboratories under Contract DA 44-009-AMC-824(T)* as a guide, the following cost estimates are presented:

1. Development costs for engine modification kits are estimated to be above \$4 million for engines having low airflow rates (3-7 pounds per second) and \$6 million to \$7 million for engines with airflow rates from 10 to 25 pounds per second. These cost estimates include a 50-hour preliminary flight rating test and a 150-hour military qualification test.
2. Procurement and installation costs of modification kits are estimated to be 50 to 75 percent of original engine cost, depending on the engine size, the lighter engine having the greater percentage increase in cost.
3. Production costs, based on a delivery rate of 100 engines per month, are estimated to be 20 to 25 percent higher than production costs of the hydrocarbon-fueled version.
4. Regenerator costs, based on a delivery rate as above, are estimated to be \$40 to \$50 per pound of regenerator.

*Solar Division, International Harvester Company, "Phase I Report: Development of an Ammonia-Burning Gas Turbine Engine", 23 July 1965.

CONCLUSIONS

From the results observed, it is concluded that:

1. The productivity of ammonia-fueled aircraft is approximately one-fourth or less that of present hydrocarbon-fueled versions; the mission radius capability is approximately one-third that of the standard versions.
2. Of the engines considered, the specific fuel consumption of the ammonia-fueled gas turbine engines is approximately 2.20 to 2.26 times that of the hydrocarbon-fueled engines, while the maximum power of the ammonia engines ranges from 15 to 16 percent higher than that of the hydrocarbon-fueled engines.
3. The use of a regenerative engine in both the hydrocarbon- and ammonia-fueled versions of the UH-1D significantly improves engine/helicopter performance; the use of a regenerative engine in the CV-7A decreases aircraft performance and only slightly increases engine performance.
4. Some form of a pressurized tank must be used for ammonia storage. With low-pressure tanks, the performance of rotary- and fixed-wing aircraft increases 30 to 35 percent over that with high-pressure tanks.
5. With the exception of a possible increase in fuel system complexity with its attendant problems, maintenance requirements for nonregenerative ammonia-fueled engines will be basically the same as current requirements for hydrocarbon-fueled engines.
6. Development costs for engine modification kits will be high and will require 3 to 4 years for development.
7. Theater-of-operation fuel and support logistics requirements (aircraft, personnel, equipment, landing fields, etc.) will increase considerably, on account of an aircraft productivity reduction of 75 percent, a range reduction of 69 percent, and consumption of four to six times the quantity of fuel (by weight) per mission.

RECOMMENDATIONS

From the results observed in this report, it is recommended that:

1. Because of limited performance of ammonia-fueled aircraft, this task be dropped from the Nuclear Powered Energy Depot concept.
2. If consideration of ammonia-fueled aircraft is mandatory, a Qualitative Materiel Development Objective be established, outlining the mission and operational requirements. Additional work in this area should include a cost effectiveness study concerned with logistics of supplying ammonia in quantities four to six times that of JP-4 fuel requirements and should also include manpower, equipment, support, and distribution requirements.
3. Research and development be continued, and in some cases be accelerated, both to obtain and to put to use the technology of the following approaches:
 - a. Variable compressor geometry.
 - b. Variable turbine geometry.
 - c. High turbine temperature technology.
 - d. High compressor-pressure ratio technology.
 - e. Regeneration.

Since the primary purpose of this concept is to reduce or eliminate hydrocarbon-fuel logistics, a reduction of 50 percent or more can be realized in current hydrocarbon-fueled gas turbine engines by utilizing one or a combination of these approaches.

4. If ammonia fuels are to be considered for other applications, an investigation be conducted to determine the feasibility of gelling liquid ammonia. Gelation of ammonia could simplify handling problems, retard the rate of vaporization, and reduce the refrigeration requirements of nonpressurized containers when storing liquid ammonia in large quantities.

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13. ABSTRACT The successful application of the Nuclear Powered Energy Depot Concept is partly dependent upon the practicability of ammonia-fueled gas turbine engines. The purpose of this investigation was to assess the feasibility of ammonia-fueled gas turbine engines in Army aircraft. In accordance with this objective, engine performance in the UH-1D helicopter and in the CV-7A fixed-wing aircraft was compared utilizing both hydrocarbon and anhydrous ammonia fuels. Aircraft fuel system requirements were investigated, and an elementary cost comparison was made for engine conversion kits and production engines. Engine maintenance was considered briefly. From this study, it is concluded that the use of ammonia as a gas turbine fuel results in considerably lower aircraft productivity than the productivity obtained from the use of hydrocarbon fuels.		

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